Comparisons between 3 fountain clocks at LNE-SYRTE

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Abstract— **Comparisons between three Cs fountains are described. All three LNE-SYRTE fountain clocks are now using a cryogenic sapphire oscillator as a starting point to generate the microwave probe signal. As a result, all three fountains have a fractional frequency instability in the 10^{-14} range at 1 s. All three fountains are also using a recently developed generation of microwave synthesizers allowing to switch the microwave probe signal without introducing detrimental phase transient. Several series of measurements have been made totalizing more than 80 days of simultaneous operation under optimized conditions of a pair of either fountains. Results of these measurements are presented. Finally, modifications of the FO2 fountain has been completed to allow simultaneous operation with Rb and Cs. Operation with Rb leads to a fractional frequency instability of $6.3 \times 10^{-14}\tau^{-1/2}$.**

I. Introduction

LNE-SYRTE is developing an ensemble of three atomic fountains. Recent work focused on implementing a new frequency distribution and a new generation of microwave synthesizers. The new scheme extends the availability of an ultra low phase noise reference derived from a cryogenic sapphire oscillator (CSO) to all three fountains. Additionally, several improvements initially demonstrated on one fountain have now been implemented on all three fountains. With them, LNE-SYRTE fountain ensemble is now able to perform repeated frequency comparison with a fractional uncertainty in the low 10^{-16} range. In this paper, we describe the most significant improvements recently made on each fountain. Next, we underline the main features of the frequency distribution scheme based on the CSO. Then , we present recent comparisons between the three atomic fountains. Finally, we will report on the modification of FO2 to allow simultaneous operation with Rb and Cs and present the first measurements made with this upgraded version of FO2-Rb.

II. New features in the three fountain clocks

A. FO1

Over the past few years, the FO1 fountain has been significantly modified, following the test of the Ramsey cavity for the PHARAO space clock [1]. One important modification has been to place again Stark plates designed to apply a static electric field in the horizontal direction. This equipment has been used to perform new measurements of the Stark shift of the clock transition in order to solve the last questions recently raised in the literature. These new measurements have been extensively described at this EFTF-FCS conference and are reported in [2]. An other modification has been the readjustment of the microwave couplings of the Ramsey cavity. Also, the laser system has been completely renewed using a new design of extended cavity laser diodes [3] with increased reliability. Finally, a 2D-MOT has been implemented to load the optical molasses.

B. FO2-Cs

In order to allow simultaneous operation will both Rb and Cs, new dual wavelength collimators have been implemented in October 2006. In these collimators, the 780 nm and 852 nm laser lights are received from two optical fibers and combined on a dichroic beamsplitter. The resulting beam is collimated using a single achromat lens. The output beams have the same sizes as previously used on FO2 (26 mm diameter at $1/e^2$ for the molasses beams). Mechanical adjustments have been done with great care to ensure several important properties: centering of output beam at the two wavelengths with respect to mechanical parts to better than 1 mm, collimation to a wavefront flatness better than $\lambda/4$ for the two wavelengths and most important, alignment of the output beams with respect to the mechanical reference surface to ~ 100 μrad for the two wavelengths simultaneously.

Following the implementation of the new dual wavelength collimators, measurements have been made to verify the alignment of the launch direction and compare it to the previous situation. Such measurements have been described in [4]. The clock frequency is measured while tilting the clock in the range of a few mrad and feeding the Ramsey cavity from either sides. As results of these measurements, we found that in the critical direction of the coupling irises of the cavity, the tilt of the launch direction was differing by ~ 100 μrad between the old and the new collimators, which is consistent which the tolerance of the initial mechanical and optical alignment of the collimators. These measurements have been exploited to

Fig. 1. FOM interrogation cavity with a thermal shield surrounding the drift region above the cavity.

optimize the tilt of the FO2 fountain with the new collimators used with Cs.

C. FOM

The transportable fountain FOM has been fully reconstructed starting shortly after a second measurement of the hydrogen H(1S-2S) transition in MPQ Garching, Germany [5], [6].

The vacuum system has been modified to implement a new Ramsey cavity, shown in fig. 1. The new cavity is 60 mm long with a 40 mm diameter. The cavity is fed by 2 independent input ports coupled by evanescent coupling. The loaded Q factor of the cavity is 17000. A thermal shield made of OFHC copper is placed above the cavity and thermally contacted to it in order to improve the homogeneity of the thermal environment. Tests performed under vacuum have shown that the temperature of the thermal shield and of the microwave cavity remain the same to better than $\sim$0.1 K under all practical circumstances. The temperature of the environment is measured with an ensemble of 7 platinum resistors which have been previously calibrated to 0.05 K by the temperature section of LNE [7]. The maximum temperature difference between the measurement points is 0.2 K which is taken as a conservative 1σ uncertainty on the thermal background temperature. Other improvements in the design of the vacuum chamber were made to minimize thermo-electric current causing fluctuations of the bias magnetic field. Currently, FOM is operated with a bias field of 80 nT.

The packaging of FOM has been reconstructed to make it easier to transport. The optical bench now uses a new type of extended cavity laser diode based on an interference filter as wavelength selective element [8], [3] rather than the traditional grating. The setup also include full digital control of the main laser parameters allowing the implementation of a fully automated relock system [8]. This system ensures continuous operation for at least one week in a basic lab environment (temperature control to ± 1 K, no moisture control).

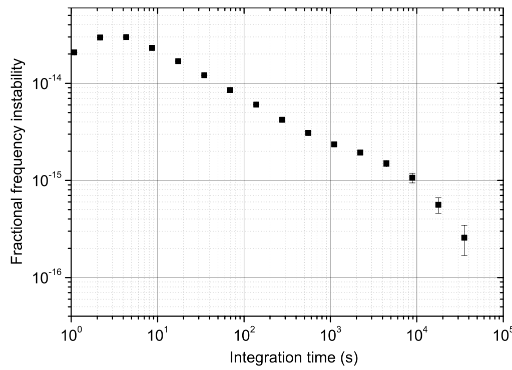

Fig. 2. Fractional frequency instability of the FOM fountain against the CSO locked to a H maser. Values are computed using the overlapping Allan variance. The short term instability is $6 \times 10^{-14} \tau^{-1/2}$

The FOM fountain now typically operates with a cycle duration of 1 s with a launch height of 600 mm leading to Ramsey fringes with a FWHM of 1.3 Hz. The FOM fountain is now fed with a low phase noise reference signal derived from the CSO as described below in section III. The microwave synthesizer has also been renewed. As a result of these improvements, FOM now operates with an improved stability, as shown in fig. 2. The plot shows the stability of FOM against the CSO locked to a H-maser. The short term instability is $6 \times 10^{-14} \tau^{-1/2}$.

Frequency shift due to cold collisions has been remeasured. It is on the order of $(-3.15 \pm 1.1) \times 10^{-15}$ for a number of detected atoms of 5×10^{5}. Test for microwave leakages has been performed using the "traditional" method based on measuring the clock frequency at an increased microwave amplitude in the Ramsey cavity. Up to an increased amplitude corresponding to $5\pi/2$ Ramsey pulses, the maximum frequency difference with $\pi/2$ pulses is 4×10^{-16}. The corresponding uncertainty is currently the main term in the accuracy budget (see section IV below).

III. New features in the frequency distribution and microwave synthesis

A. Low phase noise reference based on a cryogenic sapphire oscillator

The use of a cryogenic sapphire oscillator (CSO) as the basis for the frequency generation and distribution is one of the key point to achieve stability in the low 10^{-14} range at 1 second and to approach the quantum noise limit [9], [10]. In the past few years, new developments have been made to allow all 3 fountains to benefit from ultra low noise signal derived from the CSO as well as other improvements in the frequency generation schemes.

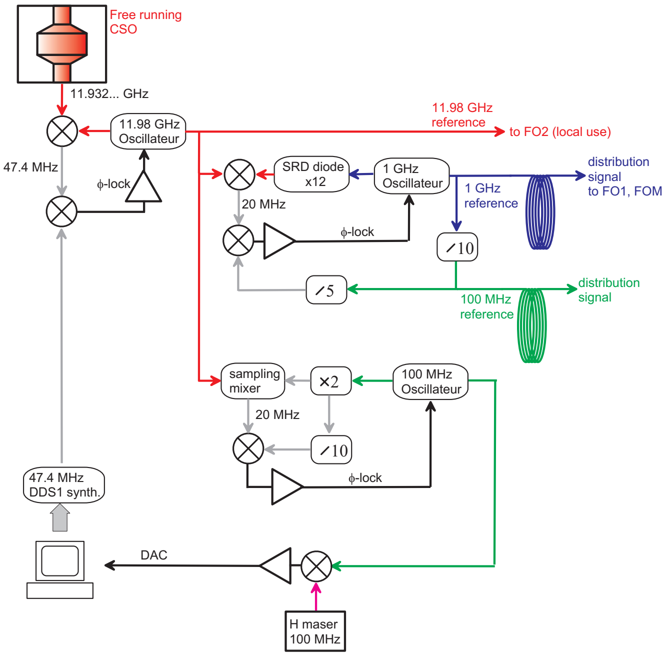

Fig. 3. Frequency generation and distribution scheme currently used in LNE-SYRTE fountain ensemble. This setup allows all three fountains (an other experiments in the lab) to benefit from the ultra low phase noise signals derived from the CSO.

The current frequency distribution scheme is depicted in fig. 3. A 11.98 GHz signal is derived from the free-running CSO oscillating at 11.932 GHz by offset phase-locking a dielectric resonator oscillator (DRO) with a direct digital synthesizer (DDS1) [11]. A divider stage converts the 11.98 GHz signal down to 100 MHz with a measured additive phase noise of -120 dBrad^2.Hz^{-1} at 1 Hz. This 100 MHz signal is miwed with the 100 MHz from a H-maser. The phase between the two signals is logged into a computer. By acting on DDS1, a digital phase-lock loop with time constant of $\sim$ 1000 s is implemented to insure long-term coherence between the H-maser and the signals at 11.98 GHz and 100 MHz derived from the CSO. A second synthesizer converts the 11.98 GHz signal down to 1 GHz with an additive phase noise of -120 dBrad^2.Hz^{-1} at 1 Hz [12]. The 1 GHz reference signal is delivered to FO1 and FOM through high stability RF cables ($\sim$ 0.1 ps.s^{-1}.m^{-1} ???). Due to the short distance between the FO2 fountain and the CSO, the 9.192 GHz source for FO2-Cs use the 11.98 GHz as the basis of the synthesis scheme. In addition to implementing the digital phase-lock loop of the reference signals to the H-maser, the computer performs continuous monitoring of several important parameters and tuning of the CSO to ensure fully automated operation of this interrogation oscillator for up to 25 days between liquid helium refills.

B. Switchable microwave synthesizers

The design of the 9.192 GHz microwave synthesizers has been described in detail in [11], [12]. In the FO2 synthesizer, the 11.98 GHz signal is divided by 4 and mixed with itself to generate 8.985 GHz which is used to offset phase-lock a DRO at 8.792 GHz with a DDS. The 9.192 GHz signal to probe the atomic transition is generated by mixing the 8.792 GHz with a 400 MHz RF signal. This scheme minimizes the amount of resonant microwave signal to reduce the induced frequency shift. In FO1 and FOM synthesizers, the previously described 1 GHz reference signal is multiplied up to 9 GHz with a step recovery diode (SRD) and used to offset phase-lock a DRO at 8.992 GHz using a DDS. The 9.192 GHz is obtained by mixing this signal with a 200 MHz generated by dividing the 1 GHz reference by 5.

Recently, these synthesizers have been improved in such a way that the probe signal can be switched off when the atomic cloud is outside the Ramsey cavity. The RF signal at 200 MHz or 400 MHz which is mixed to the DRO signal is switched off using an interferometric Mach-Zender switch [13]. In the non transmitting state, the interferometer is tuned to cause destructive interference between the two paths at the output of the interferometer. To turn the RF signal on, one of the arm of the interferometer is switched off. The design is such that the signal is crossing only passive component in the transmitting arm, in such a way that switching on is achieved without introducing a phase transient in the transmitted signal.

The evolution of the phase of the microwave signal after switching on has been measured with a heterodyne phase transient analyzer as described in [13]. This test ensures that the use of the switchable microwave synthesizer does not introduce a phase transient higher than 2 μrad.s^{-1} corresponding to a fractional frequency bias not higher than 3×10^{-17}. This switch has an attenuation of $\sim$40 dB. Comparing the clock frequency measured with and without switching the probe signal provide an unambiguous way to identify microwave leakage induced frequency shifts and to ensure that the effect of microwave leaks is negligible when the switched is used [13]. This method is now implemented both on FO1 and FO2. The FOM synthesizer has the same capability. However, measurements shown below have been performed with a continuous probe signal in FOM.

IV. Accuracy

The current accuracy of the 3 fountains is given in table I. Several improvements demonstrated on one fountain are now implemented on all of them. The main difference between FOM and other fountain comes from the fact that the pulsed microwave synthesizer is not used yet, causing the uncertainty related to microwave leakage to be higher. Also, FOM is currently not using the adiabatic passage method [14] to measure the cold collision shift. The “microwave recoil” shift arises when the quantum nature of the atomic motion is accounted for. This effect was investigated in the 1D case in [15], [16]. Recently, another approach was developed [17] where it is shown that the frequency shift is related to the focusing and defocusing of the atomic wavepacket due the magnetic dipole force seen by the atoms when crossing the Ramsey cavity. The two approaches have been compared and shown to be consistent. The second approach, however, is

TABLE I

ACCURACY OF FO1, FO2 AND FOM. THE FRACTIONAL FREQUENCY SHIFT IS GIVEN WITH ITS UNCERTAINTY IN UNITS OF 10^{-16}.

Effect	FO1	FO2	FOM
Quadratic Zeeman	1242.8 ± 0.3	1927.3 ± 0.3	210.2 ± 1.1
Blackbody	-165.0 ± 1.0	-168.2 ± 0.6	-160.45 ± 0.6
Collisions, Cavity pulling	-201.4 ± 2.4	-357.5 ± 1.0	-39.5 ± 6.7
Microwave leaks Spectral purity	0 ± 0.6	0 ± 0.5	0 ± 10
First order Doppler	0 ± 3.2	0 ± 3.0	0 ± 3.2
Ramsey & Rabi pulling	0 ± 0.1	0 ± 1.0	0 ± 0.1
Quantum motion "microwave recoil"	0 ± 1.4	0 ± 1.4	0 ± 1.4
Background collisions	0 ± 0.3	0 ± 1.0	0 ± 1.0
Total uncertainty	4	4	12

easier to extend to the actual 2D case. Work is underway to apply this approach to the actual geometry of our 3 fountains with the prospect of reducing the corresponding uncertainty down to the low 10^{-17} range.

V. COMPARISONS BETWEEN THE THREE FOUNTAIN CLOCKS

A. *Frequency stability*

Frequency comparisons between the 3 cesium fountains have been performed in November/December 2006, in April 2007 and in May 2007. During a comparison, each fountain is used as a primary frequency standard measuring the frequency of the interrogation oscillator described in section III. FO1 and FO2 continuously measure the cold collision frequency shift by alternating high atom number and low atom number configurations every 50 fountain cycles ($\sim$ 65 s). The atom number is changed using interrupted adiabatic population transfer during the state selection process [14]. For each fountain, this two series of interleaved measurements is used to correct each measurement for the collision shift. Other biases are accounted for based on measurements of several relevant temperatures (blackbody radiation shift) and of the bias magnetic field (second order Zeeman shift) several times per day. With this approach, time series of frequency measurements of the interrogation oscillator at each fountain cycle are produced for each primary frequency standard. FOM is currently handling the collision shift with a different method. The cold collision shift is measured before the comparison. The measured correction is then used over the comparison period with appropriate accounting for the possible variations in the corresponding uncertainty.

As a second step, simultaneous measurements by the two fountains under interest are extracted and the frequency difference is averaged over 100 s time intervals. These data

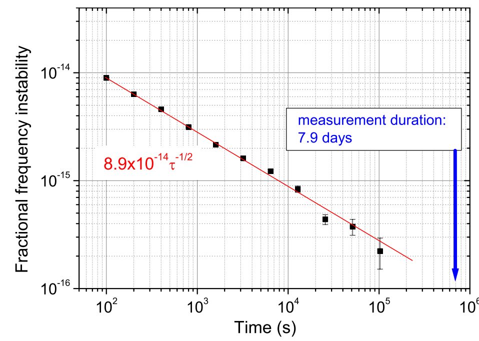

Fig. 4. Fractional frequency instability between FO2 and FOM during the November 2006 measurements (black dots). The total duration of the comparison (perfectly simultaneous operation of the 2 fountains as primary frequency standards) is 7.9 days. The combined short term instability is $8.4 \times 10^{-14}\tau^{-1/2}$.

serve as the starting point to evaluate the combined frequency instability and the average frequency difference between the two fountains.

As an example, figure 4 shows the fractional frequency instability between FO2 and FOM during the November 2006 measurements. The combined short term instability is $8.4 \times 10^{-14}\tau^{-1/2}$. In this measurement, the fractional frequency instability goes down to 2×10^{-16} at 2.2 days. Extrapolating the stability as white noise up to the total measurement duration of 7.9 days, we find a comparison uncertainty of 1.1×10^{-16} between the two primary frequency standards. As a second example, figure 5 shows the fractional frequency instability between FO1 and FO2 during the November 2006 measurements. The combined short term instability is $5.5 \times 10^{-14}\tau^{-1/2}$, similar to the 2004 measurements [18]. Here the fractional frequency instability shows a bump at the level of $\sim 6 \times 10^{-16}$ near $\tau = 1$ day. These fluctuations average down to $\sim 3 \times 10^{-16}$ at a few days. Given this behavior, we consider that the overall statistical uncertainty of this measurement is 3×10^{-16}. So far, we have not been able to clearly identify what is causing this behavior. Without this instability, the measurement uncertainty of this comparison could have been below 10^{-16}. Among all measurements reported here, several have shown this kind of instability. The data set shown in fig. 5 is the one with the largest instability.

B. *Frequency differences*

Figure 6 shows results of recent comparisons between FO1, FO2 and FOM, all made with the CSO as the interrogation oscillator. In this figure, only statistical (type A) error bars are shown. Figure 7 shows the same result with the full combined error bars (quadratic sum of the total type B uncertainty of the two fountains and of the statistical uncertainty). In these comparisons, the total uncertainty is dominated by type B uncertainties. Excepted for the last measurements, the consistency between the 3 fountains is good. This good agreement is even more significant is one consider the numerous changes that have been made between measurements and the several significant differences between the three fountains (aspect

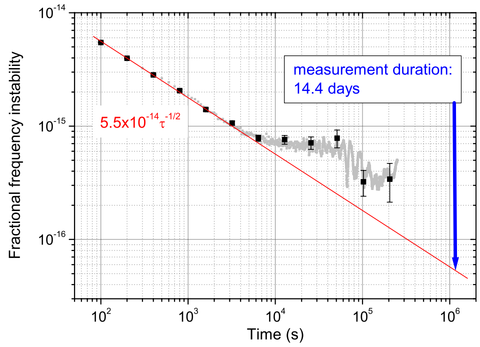

Fig. 5. Fractional frequency instability between FO1 and FO2 during the November 2006 measurements. The total duration of the comparison (perfectly simultaneous operation of the 2 fountains as primary frequency standards) is 14.4 days. The combined short term instability is $5.5 \times 10^{-14}\tau^{-1/2}$. The light gray dots show the fractional frequency instability computed for all times rather than for octaves.

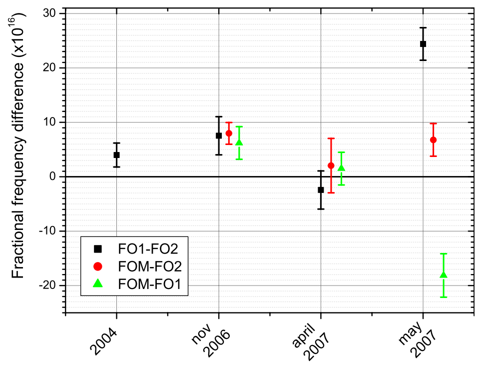

Fig. 6. Fractional frequency differences between atomic fountains FO1, FO2 and FOM. Error bars in this graph are 1σ statistical (type A) error bars. All measurements shown in this graph have been made using the CSO based interrogation oscillator.

ratios and Q-factors of the Ramsey cavities, bias magnetic field, location of the detection zone, magnitude of the collision shift,...).

The last measurements performed in May 2007 seem to indicate agreement between FO2 and FOM and discrepancy of these two fountains with FO1. This difference appeared while no significant change was made on either fountain. The cause of this difference has not been found yet despite many checks on the three fountains. Among the remaining possibilities, synchronous phase perturbations in the RF and microwave synthesis equipments need to be tested.

VI. First measurements with the FO2-Rb

As mentioned before dual wavelength collimators have been implemented on FO2 to allow simultaneous operation with Rb and Cs. A Rb 2D-MOT has been installed to load the optical molasses. A new laser system has also been implemented making use of the new design of extended cavity diode laser [3]. The laser system also uses a new laser stabilization scheme where a single laser (the probe laser) is locked to a Rb saturated absorption cell and serves as a reference. The

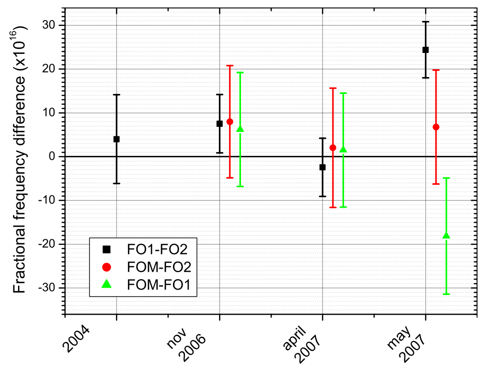

Fig. 7. Fractional frequency differences between atomic fountains FO1, FO2 and FOM with the full combined error bars. These error bars are computed as the quadratic sum of the total systematic uncertainty of the two fountains (type B uncertainty) and of the statistical uncertainty of the comparison (type A uncertainty).

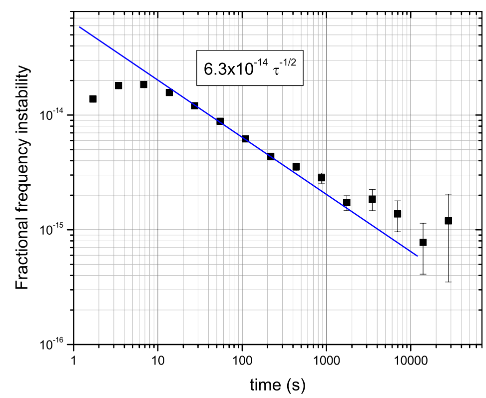

Fig. 8. Fractional frequency instability of the FO2-Rb fountain against the CSO. The short term instability is $6.3 \times 10^{-14}\tau^{-1/2}$. This is the best value measured so far with Rb.

two other lasers (master laser and repump laser) are beaten against this reference and stabilized by frequency locking the beatnote using a frequency-to-voltage converter. This scheme is meant to improve the flexibility and reliability of the laser stabilization and to ease computer controlled relock of the lasers.

Following these improvements, operation as a Rb clock has been achieved. Figure 8 shows the stability of FO2-Rb against the CSO locked to the H-maser. A short term stability of $6.3 \times 10^{-14}\tau^{-1/2}$ has been observed. This value is currently limited by detection noise (quantum projection noise and electronic noise). Loss of laser power caused by an abnormal aging of several semiconductor laser components is currently leading to reduced number of detected atoms.

Early measurements were devoted to testing the new collimators. Tilt measurements described in section II and [4] have been made using Rb. These measurements indicate that when the tilt of the fountain is optimized for Cs, the tilt of the launch direction is $\sim 200\mu$rad for Rb. This difference lies within the expectations and is sufficiently small to ensure optimized operation for Rb and Cs simultaneously.

VII. Conclusions

Recent improvements of LNE-SYRTE fountains now lead to short frequency instability below 10^{-13} at 1 s for all fountains FO1, FOM, FO2-Cs and FO2-Rb, the best observed stability ranging from $1.6\times10^{-14}\tau^{-1/2}$ to $6.3\times10^{-14}\tau^{-1/2}$. This new capability has been used to perform several stringent comparisons between the 3 fountains operated as primary frequency standards. Measurement statistical uncertainties are all in the low to mid 10^{-16} range. Most measurements have shown very good consistency between the 3 fountain clocks with fractional frequency offsets smaller than 10^{-15} and well within the total error bars. The significance of this agreement is strengthen by the numerous differences in the design and condition of operation of the 3 fountains. During the last comparison, a significant discrepancy appeared with one of the fountain. This discrepancy is currently under investigation but not explained yet despite many verifications on all three fountains. This illustrates the importance of direct and stringent comparisons between frequency standards to confirm accuracy in the low 10^{-16} range.

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