High Stability Comparison of Atomic Fountains using two Different Cryogenic Oscillators

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***Abstract*—We present a detailed characterization of two atomic clock interrogation systems based on two different cryogenic sapphire oscillators operated simultaneously. We use them as references for two accurate fountain clock frequency standards participating in international atomic time and operating both at the quantum projection noise frequency limit. The two fountain comparison down to a few 10^{-16} over 28 days demonstrates the potential of a cryocooled oscillator to replace a He refilled cryogenic oscillator.**

I. INTRODUCTION

In almost two decades, the number and the performances of cold atom fountains [1], [2], [3], [4] have drastically increased, allowing the improvement of international and national time scales, and of the realization of the second of the international system of units (SI). These frequency standards have also many applications such as the characterization of new time and frequency transfer techniques, absolute frequency measurements and fundamental physics tests.

At SYRTE, we operate an ensemble of three fountains, the two caesium fountains FO1 and FOM and the dual fountain FO2 operated simultaneously with caesium and rubidium atoms. These fountains regularly provide calibrations that are sent to the BIPM to participate to the steering of TAI, the international atomic time, and are also used to produce the new version of the French time scale UTC(OP) since 2012 [5], [6], [7]. Initially these fountains were compared using a common reference based on a BVA quartz oscillator phase locked to an hydrogen maser. The measurement stability was limited to $\sim 10^{-13}$, due to the phase noise of the oscillator because of the Dick effect [8]. This oscillator was replaced by an ultra stable reference based on a cryogenic sapphire oscillator (CSO) with liquid helium refill developed by the University of Western Australia (UWA) [9], [10]. This allows the fountains to operate at the fundamental quantum projection noise limit [11], thus reducing the averaging time needed for improving the accuracy evaluation. Our CSO is in continuous operation at SYRTE since about ten years. It presents a short term stability of $2-3\times10^{-15}$ at a 1 s integration time. Using this CSO and an ensemble of low noise synthesizers [12], [13] as a reference for FO2-Cs, we have demonstrated the best stability ever obtained with a microwave frequency standard at the level of $1.6\times10^{-14}\tau^{-1/2}$, where τ is the averaging period.

Nowadays, new developments provide alternatives to refilled liquid helium CSO for producing ultra stable microwave references. The principle of microwave generation from the optical domain based on a frequency comb laser stabilised on an ultra stable laser has been demonstrated in [14], [15]. In the experiment we performed at SYRTE, we demontrated a stability of 2×10^{-15} when comparing the output signal of our CSO to the signal produced by the stabilized optical frequency comb [14]. On the other hand, new generations of CSOs using pulse-tube cryocoolers are under development in different laboratories [16], [17], [18], [19], [20], demonstrating the improvement of atomic fountain stability [21].

This paper presents the results of an experiment performed in collaboration with FEMTO-ST institute that develops state-of-the-art cryocooled CSO systems. For a few months, one of their CSO, named Uliss, was operated at SYRTE. At FEMTO-ST institute, this CSO has demonstrated a short term stability of $6-7\times10^{-16}$ at 1 s integration time remaining below 1×10^{-15} between 1 and 10^4 s when compared to a similar device [22]. Uliss was also used as a low noise frequency reference for the ground tests of the PHARAO cold atom space clock [23] (CNES, Toulouse, France), and for a deep space network station [24] (ESA DSA 3 station, Malargüe, Argentina). The level of performances of this CSO also allowed to characherize microwave generation from the optical domain based on a solid state frequency comb [25].

This article presents the characterisation at SYRTE of two different ultra stable references, one based on our UWA CSO (named Molly) [26], [27] and the second one based on the FEMTO-ST CSO Uliss, each of them either free running or phase locked to the same hydrogen maser (H-maser). We further demonstrate the performances of these devices in a comparison between two fountains, namely the caesium and the rubidium parts of FO2 operated simultaneously (FO2-Cs and FO2-Rb) [28], each one being referenced to one of the two CSOs.

II. MEASUREMENT SETUP

The measurement set-up is shown in Figure 1. The operation of the two CSOs is based on a cylindrical monocrystalline sapphire resonator oscillating in the so called whispering gallery modes. The crystals are maintained at a low temperature of about 6 K, corresponding to the turning point of the resonance frequency slightly above liquid helium temperature. The quality factor of the resonators are of about 1×10^9. In both devices, the cavity is housed in a copper insert installed in a cryogenic system. For Molly, it is a 250 l dewar that has to be liquid helium refilled every 26 days, whereas for Uliss, the system is based on a pulse-tube cryocooler that can be operated without interruptions. The resonance frequency is about 11.932 GHz for Molly and 9.988 GHz for Uliss. The oscillation of both CSOs is maintained using a Pound-Galani servo loop, including phase, amplitude and power servo loops.

Both CSOs are equipped with ultra low noise synthesizers in order to produce reference signals phase locked to a H-maser, which allows to benefit both from the short term stability of the free running CSOs and from the long term stability of the H-maser.

The synthesizers of Molly have been described in detail in [12] and [13]. A first synthesizer produces coherent 11.98 GHz and 100 MHz signals that are phase locked to the H-maser with a time constant of a few 1000 s using a Direct Digital Synthesizer (DDS). This phase lock is based on a 100 MHz beatnote. A second synthesizer using these signals produces a 1 GHz reference signal.

Similarly, the Uliss synthesizer [29] produces a 10 GHz signal phase locked to the H-maser using a DDS, with a time constant also of a few 1000 s. A signal at 1 GHz is also generated.

In next sections, we present the characterization of the signals generated by these two different ultra stable references in terms of phase noise and frequency stability. Furthermore, we have checked the effect of the cryocooler pulse-tube on the phase of the signal generated by Uliss that could produce a frequency shift of the atomic fountain. We also verified the spectrum of the delivered signal in order to check the level of sidebands. We finally present the direct comparison between two fountains each one referenced to one of the CSOs. During this measurement, as shown in Figure 1, FO2-Cs was operated as usual, using its 9.192 GHz synthesis based on the 11.98 GHz provided by Molly, whereas the 6.834 GHz synthesis of FO2-Rb was generated using the 1 GHz signal produced by Uliss.

III. CHARACTERIZATION RESULTS

A. *Phase noise*

Figure 2 summarizes the different phase noise measurements that we have performed on the microwave signals generated by the two CSOs. We have characterized the noise of the two free running oscillators (11.932 GHz of Molly against 9.988 GHz of Uliss, black curve), of the two microwave references phase locked to the H-maser (11.98 GHz of Molly against 10 GHz of Uliss, green curve), and of the synthesisers generating these references (for Molly, 11.932 GHz against 11.98 GHz, blue curve; for Uliss, 10 GHz against 9.988 GHz, magenta curve). We have also verified the noise of the 6.834 GHz FO2-Rb synthesizer referenced on Uliss (red curve).

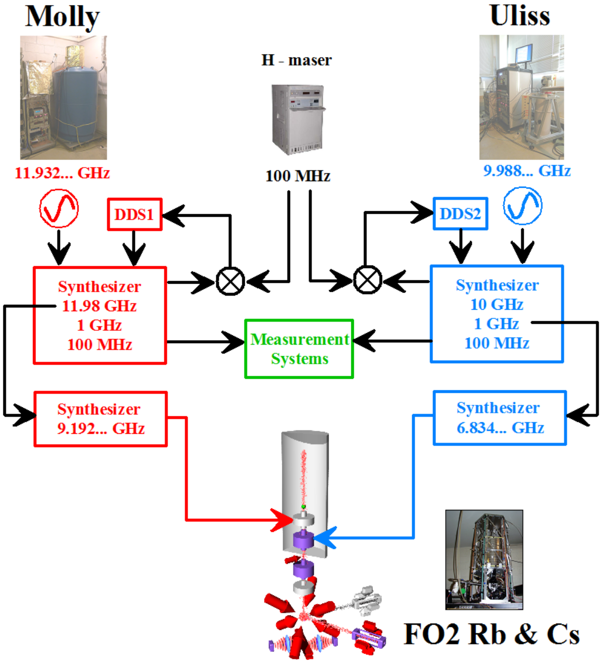

Fig. 1. Measurement setup. The two parts of FO2 using Cs and Rb cold atoms issued from 2DMOTs operate simultaneously with same cycle time.

Because there is a ~ 2 GHz frequency difference between the two CSOs, we had to implement a specific measurement system to compare the free running oscillators (see Figure 3). The two signals at 11.932 GHz and 9.988 GHz are mixed together and then down converted to the RF domain using two stages of mixing with a 1 GHz signal. The 1 GHz signal was provided by Molly, but no significant difference was observed in the results when we used the 1 GHz from Uliss. The resulting RF signal at $\sim$56 MHz is finally mixed to the output signal of a $\sim$23 MHz DDS after a frequency doubling stage. The DDS is clocked using a 100 MHz signal provided by Molly. The DDS was tuned in order to set the beatnote signal at the quadrature before being sent to a FFT analyser.

The same setup was adapted for the comparison between the two phase locked oscillators at 11.98 GHz and 10 GHz: we used the same two stages of down conversion, leading to a beatnote at 20 MHz. The beatnote was adjusted to the quadrature after mixing to the output of the DDS set to 20 MHz.

To characterize the CSOs synthesizers, we mixed the free running oscillator output to the phase locked output (11.932 GHz *vs* 11.98 GHz and 9.988 GHz *vs* 10 GHz for Molly and Uliss, respectively). The resulting RF signal was then mixed to the DDS set to the appropriate frequency: $\sim$ 48 MHz for Molly and $\sim$ 12 MHz for Uliss.

The phase noise of the 6.834 GHz FO2-Rb synthesizer referenced to the Uliss 1 GHz signal was measured using the beatnote obtained in the comparison against a backup synthesizer at the same frequency referenced to the Molly 1 GHz signal.

All these measurements were performed using a HP 3561A FFT analysing the beatnote signals adjusted to the quadrature. We verified that we obtain similar results using a Symmetricom 5125A signal analyser.

The plot of the measurement results in Figure 2 shows a phase noise of -90 dBrad^2/Hz at 1 Hz from the carrier for the comparison between the two free running CSOs (black curve), and better than -120 dBrad^2/Hz for Fourier frequencies beyond a few kHz. This corresponds to an Allan deviation of about $2-3\times10^{-15}$ at 1 s integration time. The Uliss synthesizer noise (magenta curve) presents a flicker noise of -95 f^{-1} dBrad^2/Hz between 1 Hz and a few kHz. The bump at higher frequencies is due to the lock bandwidth of the 2.5 GHz DRO used by the system but remains below -120 dBrad^2/Hz. The Molly synthesizer is slightly better for Fourier frequencies below 100 Hz (blue curve), but the phase lock loop of the 11.98 GHz DRO produces a bump of about -105 dBrad^2/Hz at about 1 kHz. These results are similar to what was obtained in 2005, when the synthesizer was put in operation [12], except for the DRO PLL gain that we have not tried to re-optimize, since the performances remained sufficiently good for application to the fountains.

The comparison between the 11.98 GHz and the 10 GHz signals of the two CSOs phase locked to the H-maser presents a phase noise equivalent to that of the free running CSOs for frequencies below 100 Hz. For higher frequencies, it is limited by the Molly synthesizer. The phase noise measured at 6.834 GHz is equivalent to a flicker noise of -87 f^{-1} dBrad^2/Hz between 1 Hz and 1 kHz and limited by the backup synthesizer for higher frequencies. This is equivalent to a frequency noise of $\sim 5\times10^{-15}$ at 1 s integration time for the combination of both synthesizers. This will produce a negligible contribution to the stability of FO2-Rb, as will be seen in section IV.

B. Stability

Figures 4 and 5 show a summary of the various stability measurements performed using Uliss and Molly. All the curves correspond to overlapping Allan deviations measured in a bandwidth of a few Hz.

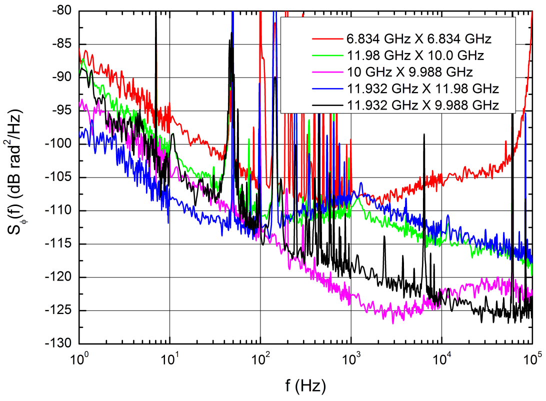

Fig. 2. Phase noise of the comparison between the two free running CSOs (black), of the CSO synthesizers (blue for Molly, pink for Uliss), of the comparison between the two phase locked CSOs (green), and of the comparison between two 6.834 GHz synthesizers referenced to 1 GHz signals provided by Molly and Uliss, respectively, to be used by FO2-Rb (red). The results are given at the measurement frequency, without rescaling.

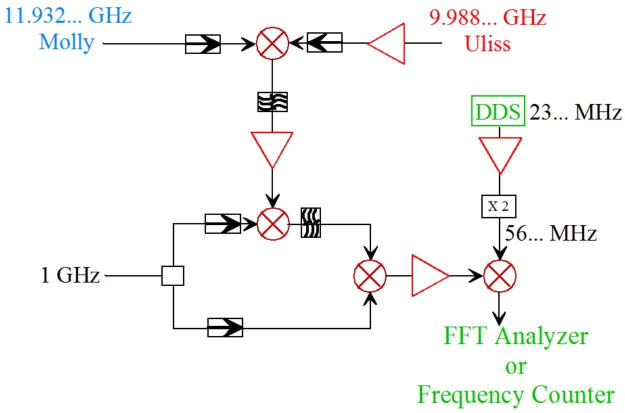

Fig. 3. Measurement system for phase noise and stability characterization of the microwave outputs of the two CSOs.

The red and blue curves correspond to comparisons Uliss *vs* H-maser and Molly *vs* H-maser, respectively, measured using a 100 MHz phase comparator (Timetech PCO). The stability at 1 s is about 8×10^{-14}, because in actual practice this is not the direct 100 MHz output of the H-maser that is distributed to the CSOs, but the output of a BVA/VCXO 100 MHz synthesizer phase locked to the H-maser. The bump at a few seconds corresponds to the time constant of the phase lock loop of the BVA quartz oscillator to the H-maser. The stability decreases down to below 10^{-16} for an averaging period of about 1 day, demonstrating the good operation of the phase lock loop of both CSOs to the H-maser. Due to this phase lock, a small bump is observed at averaging periods of about 3000 s. We note that this effect is slightly smaller for Uliss than for Molly because of a lower frequency drift when free running. The red and blue squares on the graph, obtained while analysing the in loop error (beatnotes at 100 MHz) give exactly the same results.

The black squares in Figures 4 and 5 correspond to the statistical analysis of the frequency corrections applied to the DDS of the two phase lock loops to the H-maser. This gives an estimation of the CSOs frequency drift, that is about $10^{-13}/d$ for Molly and $\sim 7\times10^{-15}/d$ for Uliss. The Allan deviation values in these curves are not relevant for averaging periods below 1000 s, because the noise is filtered by the phase lock loops.

The green curves in Figures 4 and 5 give the comparison between the 100 MHz outputs of the two CSOs as measured by the PCO. It is limited by the instrument noise until averaging periods of a few hundred seconds (noise floor of about $2\times10^{-14}\tau^{-1}$).

The purple curve reproduced in Figures 4 and 5 gives

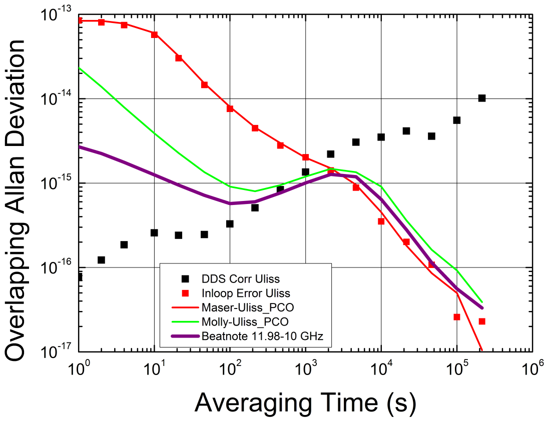

Fig. 4. Stability characterization of Uliss CSO, as measured either in the microwave domaine, or using a 100 MHz phase comparator (PCO), and as analysed from the inloop error and the DDS corrections.

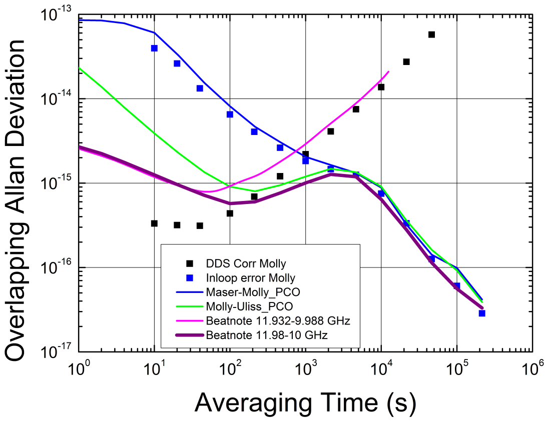

Fig. 5. Stability characterization of Molly CSO, as measured either in the microwave domaine, or using a 100 MHz phase comparator (PCO), and as analysed from the inloop error and the DDS corrections.

the Allan deviation obtained in the comparison between the 11.98 GHz and the 10 GHz signals from Molly and Uliss, respectively. This measurement was performed with the setup described in Figure 3 adapted for the stability characterization: the $\sim$ 20 MHz DDS was adjusted to get a beatnote at about 65 Hz and the output of the last mixer is AC coupled using a 4 Hz bandpass filter centred at this frequency. The resulting beatnote frequency is measured using a frequency counter (Agilent model 53132A). We also performed several tests using the 5125A Symmetricom signal analyzer measuring directly the $\sim$ 20 MHz beatnote and obtained the same results. The comparison of the microwave outputs of the CSOs shows a stability at 1 s as low as $2-3\times10^{-15}$ and reaches 6×10^{-16} for averaging periods of about 100 s. For longer integration times the stability increases to about 10^{-15}, due to the bump of the phase lock loop, and decreases back to lower than 10^{-16} for averaging periods of 1 day, as for the measurements performed with the 100 MHz signals.

The magenta curve in Figure 5 shows the stability of the comparison between the two free running CSOs (11.932 GHz *vs* 9.988 GHz). It was measured with the previous setup except that the DDS was set to $\sim$ 23 MHz and then frequency doubled. We obtain the same short term stability as for the comparison 11.98 GHz *vs* 10 GHz of the two CSOs phase locked to the H-maser, for averaging times up to a few tens of seconds. For longer periods the stability is degraded by the frequency drift of the CSOs, dominated by that of Molly. This is in agreement with the analysis of the frequency corrections applied to the CSOs synthesizers.

C. Phase transient

We have characterized the effect of the cryocooler pulse-tube of Uliss on the output signal phase. This verification was important because there could have been a phase transient transmitted to the interrogating signal of the fountain that could produce an additional frequency shift. This characterization was performed using the nominal and backup 6.834 GHz synthesizers of FO2-Rb referenced to the 1 GHz outputs of Uliss and Molly, respectively. We used the heterodyne phase transient analyser described in [30] regularly operated to verify the absence of synchronous perturbations on our fountains. This device allows to average the phase of the signal synchronously to the pulse-tube of the cryocooler. For this test, the trigger was produced from one of the internal temperature sensors of Uliss, that is sensitive enough to observe thermal variations inside a cycle of the cryocooler pulse-tube: we used one of the analog output of the resonator temperature servo loop that has been amplified.

Figure 6 shows the results of two phase transient measurements obtained after averaging over about 1 day, separated by several months. The duration of the measurement window is about 1.4 s, which corresponds to two cycles of the pulse-tube. We clearly see an impact of the resonator thermal transient on the signal, which can reach several tens of μrad (see black curve in Figure 6). We observed that the shape and the amplitude of these transients varied in time, probably because of variations in the pulse-tube regime. Such phase variations could lead to frequency shifts of the fountain clock of several 10^{-15} if they were synchronous to the fountain cycle time. Fortunately, because FO2-Rb cycle time is about 1.6 s, the perturbation will average down to zero. This level of perturbation will also have a negligible impact on the frequency stability of the fountain, that is at the level of a few $10^{-14}\tau^{-1/2}$.

D. Spurious characterization

We have also checked the spectral purity of the 6.834 GHz output of the FO2-Rb synthesiser referenced to Uliss using a 1 Hz resolution spectrum analyser. This has been done with the synthesizer connected to the fountain to be as representative as possible of the fountain operation. The main spurious lines are at a frequency of 100 Hz and its harmonics. As can be seen in Figure 7 these sidebands are 65 dB below the carrier and quite

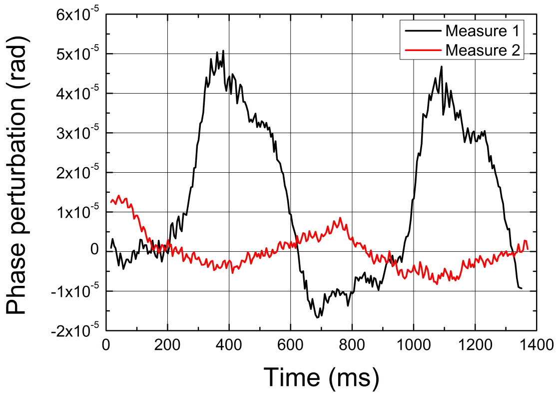

Fig. 6. Two examples of phase transients observed on the 6.834 GHz signal referenced to Uliss averaged synchronously to the pulse-tube cycle time.

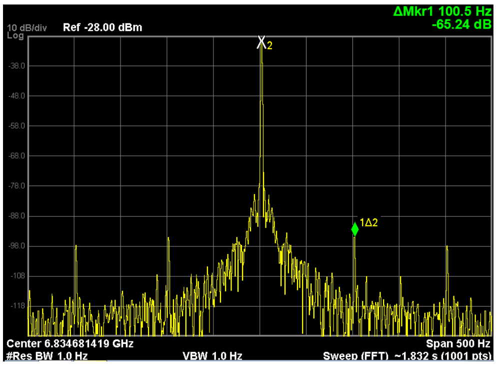

Fig. 7. Spectrum of the 6.834 GHz FO2-Rb synthesizer referenced to Uliss 1 GHz signal.

symmetric. This corresponds to a frequency shift well below 10^{-16}.

IV. FOUNTAIN OPERATION

To fully demonstrate the operation of the cryocooled CSO as a fountain reference, we have performed a frequency comparison between FO2-Rb operated using its synthesizer referenced to Uliss, against FO2-Cs operated as usual, using its interrogating signal based on Molly's reference. During these measurements, both CSOs were phase locked to the same H-maser. Figure 8 presents the overlapping Allan deviations that we have obtained after 28 consecutive days of measurement. The measurement was interrupted only a half day for a liquid helium refill of Molly. The red and blue dotted curves give the individual stability of each fountain after averaging the data over 100 s. For FO2-Rb, the stability is the same as when operated using Molly as reference. The graph shows short term stabilities of $4.6 \times 10^{-14}\tau^{-1/2}$ for FO2-Rb$-$Uliss and $4.3\times10^{-14}\tau^{-1/2}$ for FO2-Cs$-$Molly. These stabilities include the fact that we alternate between full and half atomic density in order to evaluate the effect of cold collisions in real time, which corresponds to fully accurate operation of the fountains.

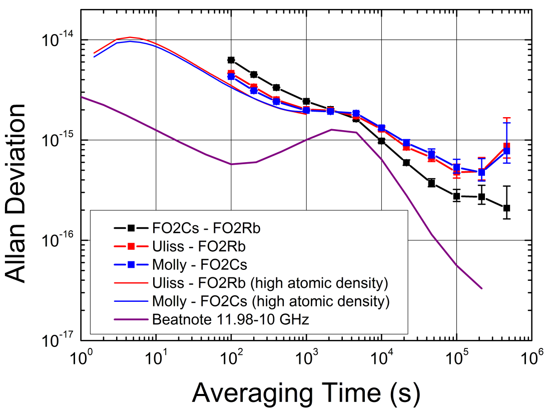

Fig. 8. Stabilities of two fountains referenced to the two CSO based systems: stability of FO2-Rb referenced to Uliss and of FO2-Cs referenced to Molly operated either at full atomic density or in alternate mode (full/half atomic density) to evaluate the cold collisions; stability of the comparison between FO2-Cs and FO2-Rb.

If we take full density measurements only (red and blue lines), the short term stability is improved to $3.5 \times 10^{-14}\tau^{-1/2}$ and $3.4 \times 10^{-14}\tau^{-1/2}$ for the two comparisons, respectively. The observed stabilities present only a small bump at about 3000 s due to the phase lock loop of the CSOs to the H-maser. The Allan deviations reach the 10^{-16} range after an averaging time of $\sim 10^4 s$. For averaging periods higher than a few days, the Allan deviations show the frequency drift of the H-maser, that is about $10^{-16}/d$. This is removed if we calculate the differences of the fountain data over synchronous intervals, as can be seen on the black squares Allan deviation curve that reaches 2×10^{-16} after averaging over 5 days. The difference FO2-Cs$-$FO2-Rb averaged over the total measurement duration is 1.6×10^{-16}. This result is fully compatible with the total systematic uncertainty of 4×10^{-16} from the fountain accuracy budgets, and agrees with measurements performed before and after, using Molly as the reference for both fountains.

V. CONCLUSION

This paper presents a full characterization of two different type ultrastable sapphire oscillator references, one based on a refilled liquid helium CSO and the second using a pulse-tube cryocooled CSO, both phase locked to the same H-maser. We have measured the phase noise and the Allan deviation of the oscillators either free running or stabilized, reaching a short term stability at the level of $2-3\times10^{-15}$ at 1 s. We have also verified that the performances of the associated synthesizers are consistent with this result. We have checked the operation of the cryocooled CSO in terms of phase transient and spectral purity that could have produce systematics in a fountain operation. Furthermore we have demonstrated the operation of two fountains each one referenced to one of the two CSOs leading to a short term stability of $\sim 3.5\times10^{-14}\tau^{-1/2}$ when operated at high atomic density. At last, we have performed a 28 days quasi continuous fountain frequency comparison reaching a stability of 2×10^{-16} in fully accurate operation, including cold collisions evaluation. The result was in complete agreement with the accuracy budgets of the fountains and with earlier and later comparisons using the SYRTE CSO for both fountains.

At SYRTE, we are currently improving the long term operation of ultrastable microwave generation based on an optical frequency comb stabilized to an ultrastable laser as a backup reference oscillator to our CSO for the fountains operation. This work performed in collaboration with FEMTO-ST Institute demonstrates that a cryocooled CSO can also provide an alternative for this kind of applications.

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