Cold-atom-based Commercial Microwave Clocks at 1×10^{-15} Relative Instability Over More than One Month

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***Summary*—We present several commercial microwave clocks, turnkey product based on laser cooled atoms dedicated for continuous long-term operation, that maintain an extreme frequency stability of 1×10^{-15} over more than one month.**

Keywords*— *Microwave clocks, cold atoms, isotropic cooling

I. INTRODUCTION

Microwave clocks have reached outstanding performances in both short- [1] and long-term frequency stability [2], as well as accuracy [1]. So far, these results have been obtained with room-size cold-atoms fountain clocks, but efforts have been made to develop more compact and fully autonomous setups for space [3] or civil applications.

Our MuClocks are the continuity of the Horace project based on isotropic cooling of cesium atoms in a spherical copper cavity that started at SYRTE in 2001 [4] and showed a fractional frequency stability of 2.2×10^{-13} at 1 s [5] and 3.2×10^{-15} at 20 000 s [6]. A follow-up technology project called Rubiclock was initiated in 2011 in collaboration between SYRTE, LP2N (Bordeaux), and Muquans. The main difference lied in the use of rubidium in order to benefit from a lower cold collisions shift [7-8] and frequency doubled telecom lasers [9] developed by Muquans. Rubiclock demonstrated similar performances with 3.7×10^{-13} at 1 s and 3.3×10^{-15} at 100 000 s on ground and was operated in both micro-gravity and an airborne, noisy environment [10].

Our MuClocks are the commercially developed versions of these prototypes destined to propose turnkey autonomous devices that reach 1×10^{-15} over long periods of integration. As a first milestone, a frequency instability of 1×10^{-15} over one month was fixed to maintain a frequency stability in between two updates of the BIPM circular-T. This milestone has been reached and is presented in these proceedings. A detailed technical study is ongoing to further improve performances to a short-term instability of 3×10^{-13} at 1 s and a long-term instability below 1×10^{-15}. A complete accuracy budget is also under preparation with a targeted accuracy in the 5×10^{-15} range. In parallel, Muquans, which has recently merged with iXblue, has started to produce second generation MuClocks in order to propose more compact and cost-effective solutions.

Sponsors: CNES, ESA, First-TF, BPI

II. WORKING PRINCIPLE

Our MuClock is based on laser cooled atoms which allow to extend the duration of the spectroscopy and better control the systematic effects.

A. Temporal Sequence

The apparatus has been described elsewhere [11]. It is based on a copper cavity, which is first used as an integrating sphere for isotropic cooling where 10^7 atoms are cooled by optical molasses to sub-Doppler temperatures. The free-falling atoms are then interrogated by microwave pulses delivered to the resonant cavity in a so-called Ramsey sequence with T_R = 40 ms. Eventually, the atoms in the $|F=2\rangle$ hyperfine state are detected by absorption of a vertical light column. By the means of atom recapture, we increase the duty cycle to repetition rates between 5 and 10 Hz.

B. Short-term noise sources

The frequency stability of the MuClock can be explained by two fundamental noise sources that cannot be overcome in this setup [11]. They appear during detection with the statistical shot-noise from thermodynamics (SN) [12] and quantum projection noise (QPN) [13]:

$$\sigma_N = \sqrt{\sigma_{\mathrm{SN}}^2 + \sigma_{\mathrm{QPN}}^2} = \sqrt{N}, \qquad (1)$$

where N is the actually detected atom number in the $|F=2\rangle$ state only and σ_N the atom number noise scaling as $\sqrt{N}$. Nonetheless, technical noise sources may contribute leading to a detection noise of:

$$\sigma_{\mathrm{det}} = \sqrt{\sigma_{\mathrm{floor}}^2 + \sigma_N^2 + \sigma_{\mathrm{tech}}^2}, \qquad (2)$$

where σ_{floor} is a technical noise floor including all electronics, photonics and vapor related noise sources, while $\sigma_{\mathrm{tech}} = \alpha N$ is a technical noise proportional to the atom number mainly limited by laser frequency and intensity fluctuations. Finally, the last noise source arises from the local oscillator phase noise through the so-called Dick effect [14]. Thus, we define the total noise of the detected atoms number:

$$\sigma_{\mathrm{tot}} = \sqrt{\sigma_{\mathrm{det}}^2 + \sigma_{\mathrm{Dick}}^2}, \qquad (3)$$

with σ_{Dick} the Dick effect contribution converted to atom number noise.

III. RESULTS

In several measurement campaigns we have compared our MuClocks with different ultra-stable frequency references at SYRTE (1×10^{-13} at 1 s and reaching few 10^{-16} in the long-term, with a drift of 1.3×10^{-16}/day), at CNES (8×10^{-14} at 1 s and reaching 2.5×10^{-15} at one day, with a drift of 1.69×10^{-16}/day) and at a customer site. (The bracketed values give the independently measured performances of the local frequency reference.) MuClocks offer two operation modes: locking the local oscillator to the atoms (master clock mode) or locking the MuClock local oscillator to an external reference and accounting the frequency difference with respect to the atoms (frequency meter mode). In the following, we present the results from the frequency meter mode.

A. Short-term frequency instability

The clock short-term instability is described by [15]:

$$\frac{\sigma_{\delta\nu}}{\nu_0} = \frac{1}{\pi}\frac{1}{Q_{\mathrm{at}}}\frac{1}{SNR}\sqrt{\frac{T_C}{\tau}}, \qquad (4)$$

where $Q_{at} = \nu_0/\Delta\nu$ is the quality factor of the atomic resonance, with $\Delta\nu = 1/(2T_R)$ for a Ramsey interrogation and $\nu_0 = \nu_{HFS}$ with no bias, SNR = CN/σ_{tot} includes the fringe contrast C, the atom number N and its noise σ_{tot}. T_C is the cycle duration, and τ is the integration time. With our experimental parameters, we calculate for each of our clocks short-term instabilities ranging from $\sigma_{\delta\nu}/\nu_0 = 3.5\times10^{-13}$ to 5.4×10^{-13} at $\tau = 1$ s depending on their fine tuning. These results are in relatively good agreement with the measurements presented in Fig. 1.

B. Long-term frequency instability analysis

We realized several one-month runs to measure the long-term frequency stability of the different clocks. Each measurement was realised at a different location. All MuClocks demonstrated $\sigma_{\delta\nu}/\nu_0 = 1\times10^{-15}$ in 2 to 3 days of integration where they reached a flicker floor that holds for more than one month (see Fig. 1). The error bars are not plotted in Fig. 1 for the sake of clarity. Fig. 2 presents a proof-of-principle measurement of a very-low drift maser with MuClock A01. During this measurement, the maser frequency drift of 1.69×10^{-16}/day was measured independently. Removing this frequency drift from the MuClock values improves the long-term frequency stability, as shown with the red line in Fig. 2. Longer runs are planned to evaluate the long-term frequency stability the MuClocks. Some systematic shifts were investigated to identify their impact on the long-term frequency stability. They are presented in the following.

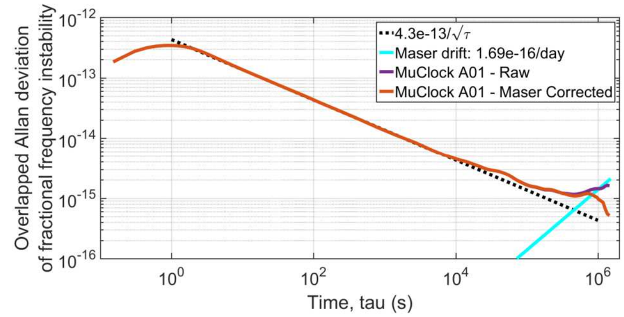

Fig. 2. Allan deviation of the fractional frequency instability of MuClock A01 limited by a maser drift.

1) Quadratic Zeeman shift

The second-order Zeeman shift [16] is extracted through a magnetic field measurement done by tuning the microwave frequency to one of the magnetic field sensitive transitions once every 500 shots. In order to account for the spatial field inhomogeneity, 1-ms long pulses are used whose frequency resolution is much wider than the magnetic inhomogeneity. The vertical gradient is finally measured for different free-fall

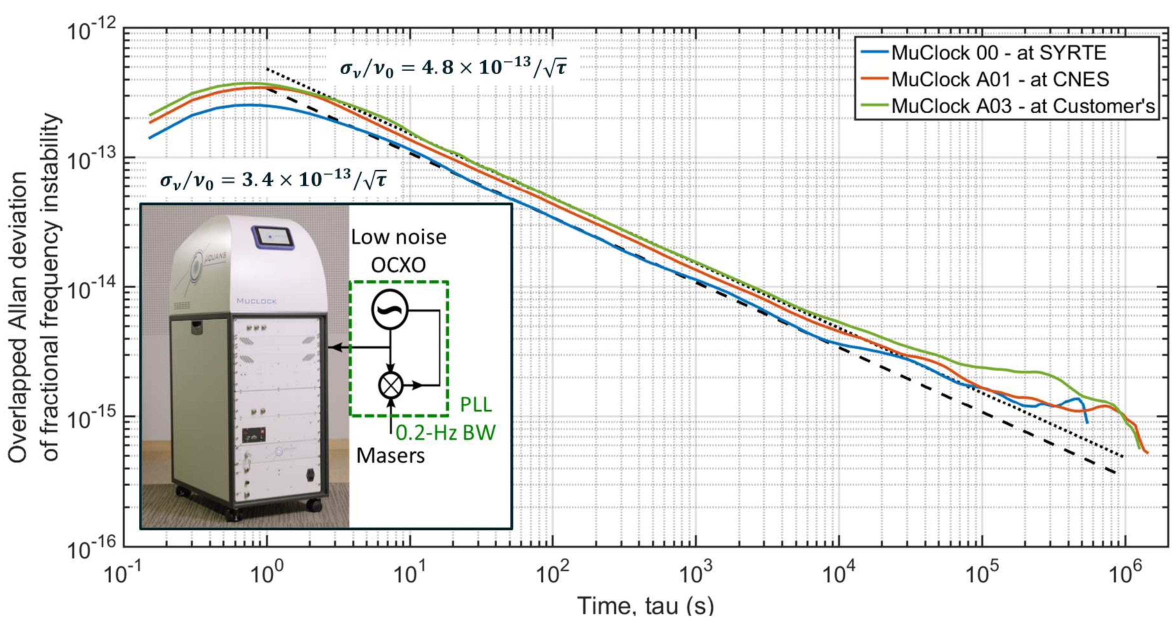

Fig. 1. Allan deviation of the fractional frequency instability of our MuClocks. Inset: measurement method with the local oscillator locked on a maser.

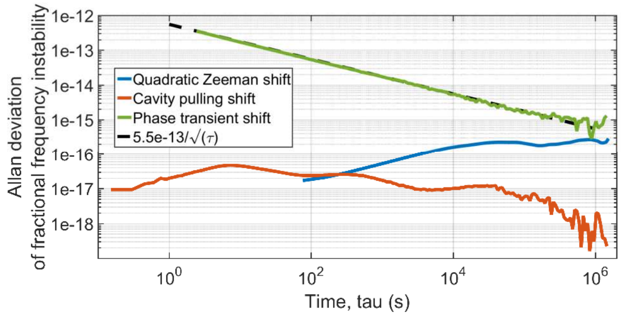

Fig. 3. Allan deviation of the fractional frequency instability due to the main systematic frequency shifts during a one-month run of MuClock A01.

durations. The effective magnetic field seen by the atoms reaches a stability of 0.3 nT peak-to-peak over one month with gradients smaller than 0.4 nT/cm. The corresponding effective quadratic Zeeman shift is plotted in blue in Fig. 3 and reaches a long-term stability below 3×10^{-16}, making this contribution small compared to our targeted long-term frequency stability.

2) *Cavity pulling*

Cavity pulling is defined as a shift of the clock transition due to an interference between resonant photons injected into the cavity and photons emitted by the atoms themselves [17]. It was formerly characterized on our MuClocks exhibiting at resonance a cavity pulling slope of -1.0×10^{-8} Hz of clock transition per Hz of cavity detuning [11]. It has a major dependency on the cavity frequency detuning from the atomic resonance. Once the cavity detuning is set at resonance, its dependency on the atom number is nulled. Then, the main contributor is the cavity frequency instability which we also measure during clock operation. The cavity resonance is stabilized to within +/- 350 Hz and integrates down to 1 Hz. Its contribution as cavity pulling is plotted in red in Fig. 3 and shows a negligeable contribution of 1×10^{-18} on long timescales.

3) *Shifts from phase transient*

Phase transients on the microwave signal imprinted onto the atoms during the two separated Ramsey pulses appear as frequency shifts. Microwave phase transients arise from any thermal dependence of the signal transmission up to the atoms. These transients are not specified and should be measured *in-situ* in order to appreciate their impact, both, in terms of accuracy and long-term stability. A dedicated test bench has been developed on a similar architecture as in [18]. It exhibits a phase resolution of 200 µrad rms at 1 shot which integrates below 2 µrad rms. A measurement of the phase transient has been realised in parallel of the one-month run of MuClock A01. Its stability is shown in Fig. 3 reaching less than 1×10^{-15} after one month of integration. Longer measurements are necessary to conclude on the possible long-term limitation of the phase transient shift.

C. *Accuracy budget*

Measurements for preliminary accuracy budgets have been made over the past years. A dedicated study has been started on our two first prototypes to deliver a more precise evaluation. In addition to the long-term contributions detailed in the previous section, Rabi and Ramsey pulling as well as the distributed cavity phase shifts are the next systematics under fine evaluation.

IV. Conclusions

To conclude, we have developed several commercial cold-atom-based microwave clocks which are autonomous turn-key products. They reach short-term fractional frequency instabilities ranging from 3.2×10^{-13} to 4.8×10^{-13} at 1 s and long-term instabilities of 1×10^{-15} after more than a month of measurement for all units. Their accuracy budget is still under evaluation with a targeted accuracy in the 5×10^{-15} range.

Acknowledgment

The authors would like to thank the former contributors to the Horace and Rubiclock projects, as well as the work that has been achieved by the entire iXblue Quantum Sensors team. Special thanks to D. Holleville and R. Szmuk for their former contributions and to P. Rosenbusch for proofreading this manuscript as a new member of our team. Helpful discussions with F.-X. Esnault, L. Lorini, M. Abgrall, S. Bize, K. Gibble, Ph. Laurent, G. Santarelli, M. Lours, G. de Giovanni, S. Guérandel and N. Dimarcq are gratefully acknowledged. We also acknowledge the support from CNES, ESA, First-TF and BPI.

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