# Accuracy assessment of a commercial cold-atom Rb clock: a use case within the Qu-Test project


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***Abstract*** **—A commercial cold-atom Rb clock, developed by Exail with a stability of $1 \times 10^{-15}$ [1-2], is hosted at LNE-SYRTE to consolidate an accuracy budget through a use case within the Qu-Test project. Long-term evaluation of critical frequency biases is ongoing and will go on for several months.**



***Keywords—Accuracy budget, microwave clock, cold atoms, Ramsey pulling, microwave phase transient, position phase gradient***


## I. THE HORIZON EUROPE PROJECT QU-TEST

In recent years, the technologies issued from the "second quantum revolution" start to be exploited in the domain of computing, communication and sensing. The Horizon Europe project "Qu-Test", co-funded by the European Commission, aims to federate a network of testbeds and industrial users to support testing and validation services in the domain of quantum technologies.

The LNE-SYRTE, located in Observatoire de Paris, is a member of the Qu-Test consortium, offering testing facilities for quantum sensors in the domain of Time-Frequency and Gravimetry Metrology. The Qu-Test activity includes, in the early stage of the project, some "use cases" to validate the testbeds with respect to the needs of industrial partners.

## II. COLD RB CLOCK ACCURACY ASSESMENT USE CASE

Both partners of the Qu-Test network, SYRTE and Exail, contribute to the project with a use case: the assessment of an accuracy budget for a commercial cold-atom Rb clock (called MuClock), developed by the Exail's Quantum Systems division. The MuClock is a commercial clock already available for customers. Now, it is offered to customers with stability specifications, but the clock can potentially provide better accuracy performances than other products available on the market. Improvement of medium- and long-term stabilities requires deep knowledge of the biases induced by environmental perturbation. Moreover, accuracy evaluation is important for some specific users when the clock frequency cannot efficiently be "steered" by an external frequency reference and is therefore used as a local master clock.

### *A. Use-case plan*

The use-case plan is to directly compare a prototype of MuClock (referred to as MuClock 00), located at the LNE-SYRTE laboratory, to LNE-SYRTE's local frequency reference. Such a frequency reference is issued from a H-maser, which is continuously compared with an ensemble of atomic fountains primary frequency standards. This reference has a stability better than $\sigma_{\delta\nu} < 2 \times 10^{-13}$ at 1s (expressed in term of Allan deviation) and an accuracy of $u = 3 \times 10^{-16}$. Such performances are adequate for the accuracy assessment of the MuClock.

The MuClock is hosted in a temperature-controlled room, where the temperature is kept stable within ± 1°C. Operation of the clock is completely manageable from remote through a secure network connection. The MuClock is expected to stay at LNE-SYRTE for a long period (more than 8 months) where comparison measurements with respect to the absolute frequency reference alternate with experiments focused on the evaluation of specific MuClock's frequency biases.

### *B. Preliminary Accuracy evaluation*

Prior to these accuracy assessment phase, a preliminary accuracy budget for MuClock 00 was established. Most of the biases have been evaluated by theoretical or empirical considerations and using differential measurements. Table 1 reports the MuClock 00 accuracy budget just before its arrival at LNE-SYRTE.

## III. FREQUENCY MEASUREMENT AND ACCURACY ASSESSMENT

### *A. Assessment at arrival*

Before shipping, MuClock 00 has been tested at Exail's premises to verify the functional operation and its medium- and long-term stabilities. This test stage has demonstrated the robustness of remote operation and confirmed the stability prerequisite for the use case (stability better than $\sigma_{\delta\nu} < 2 \times 10^{-15}$).

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After shipment, the MuClock frequency has been compared to the LNE-SYRTE reference for a period of 14 days. The stability of this run was nominal (*Fig.1*).

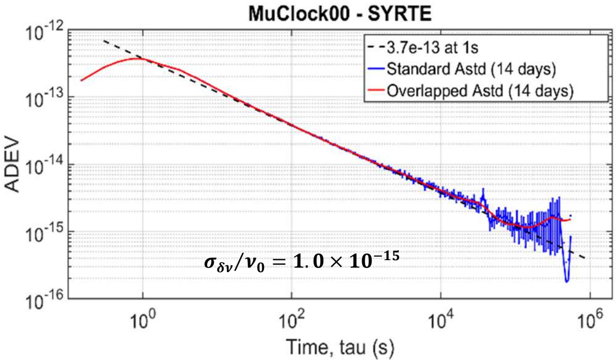


*Fig. 1. Allan deviation of the MuClock 00 frequency measured against the LNE-SYRTE reference.*

The measured absolute frequency difference (MuClock-Ref(LNE-SYRTE)) is $\delta\nu = -2.0 \times 10^{-14}$ with a statistical uncertainty of $\sigma_{\delta\nu} = 1.0 \times 10^{-15}$. This result agrees with the uncertainty established during the preliminary accuracy evaluation which gave a systematic uncertainty of $u = 8.5 \times 10^{-14}$ .

## IV. EVALUATION OF CRITICAL FREQUENCY BIASES

The largest contributions to MuClock 00's uncertainty come from three effects: Ramsey pulling, microwave phase transients and spatial phase gradients. All these three effects will be re-evaluated during the next period with the goal of reducing the overall associated uncertainty to $u < 5 \times 10^{-14}$.

### *A. Ramsey pulling*

MuClock 00 is potentially exposed to non-negligible Ramsey pulling, due to atom populations in the $|m_F \neq 0\rangle$ states and a non-zero angle between the microwave interrogation field and the quantization magnetic field [3-5]. This angle is expected to finely depend on the atom position.

Thus, the atom cloud distribution and microwave cavity field have both been measured and simulated. In the worst-case scenario, the pulling can be as large as $\delta\nu_{RP} = \pm 2 \times 10^{-14}$ . However, the effect depends on the coherence between $|m_F \neq 0\rangle$ and $|m_F = 0\rangle$ states (owing to the off-axis elements of $\rho_{0\pm1}$ density matrix) which could be washed out by several effects like the magnetic field inhomogeneities for instance. Finer measurements of this frequency biases are still in progress.

### *B. Microwave phase transient*

MuClock 00 works in a pulsed regime with a Ramsey interrogation scheme while the atoms stay in the interrogation area during the whole Ramsey process. The phase of the applied microwave in the cavity can experience transients causing a phase shift between the two Ramsey pulses that translates into a clock frequency shift [6]. These phase transients require to be finely measured.

A phase transient measurement bench (*Fig.2*), developed by Exail, showed an accuracy of 1 µrad and a temporal resolution below 1 µs. It is currently in preparation to be shipped to LNE-SYRTE. Once the measurement is done on MuClock 00, the accuracy evaluation of the phase transient shift should be lowered to the $u_{PT}$~$5 \times 10^{-15}$ level, as demonstrated on other MuClocks.

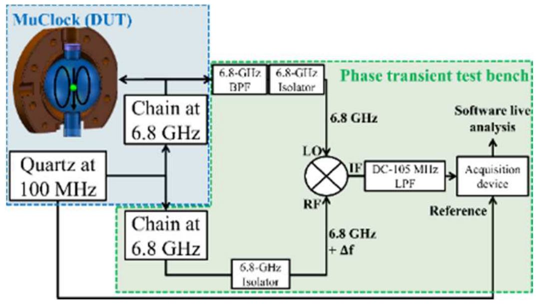


*Fig. 2. Phase transient measurement bench developed by Exail and funded by LabEx FIRST-TF (ANR-10-LABX-48-01).*

| ***Physical effects*** | ***Mean frequency offset,*** $\delta\nu$ $(\times 10^{-15})$ | ***Uncertainty,*** $u_{\delta\nu}(\times 10^{-15})$ | ***Stability,*** $\sigma_{\delta\nu}$ $(\times 10^{-15})$ |
|---|---|---|---|
| **Quadractic Zeeman shift,** $\delta\nu_{QZ}/\nu_0$ | 2 204.2 | 1 | 0.3 |
| **Cavity pulling shift,** $\delta\nu_{CP}/\nu_0$ | 0 | 5 | <0.002 |
| **Microwave phase transient shift,** $\delta\nu_{PT}/\nu_0$ | 109.9 | 80 | <1 |
| **Dynamic end-to-end cavity phase shift,** $\delta\nu_{DECP}/\nu_0$ | 17.5 | <17 | TBD |
| **Rabi pulling shift,** $\delta\nu_{RP}/\nu_0$ | -0.01 | <1 | <0.02 |
| **Ramsey pulling shift,** $\delta\nu_{RamP}/\nu_0$ | 16.9 | <20 | 0.01 |
| **Dispenser blackbody radiation shift,** $\delta\nu_{BBRD}/\nu_0$ | -1.9 | <1 | 0.4 |
| **Cavity blackbody radiation shift,** $\delta\nu_{BBRC}/\nu_0$ | -18.8 | <2 | <0.02 |
| **Position phase gradient shift,** $\delta\nu_{PPG}/\nu_0$ | 37.5 | TBD | TBD |
| **Direct microwave leakage shift,** $\delta\nu_{ML1}/\nu_0$ | 1.6 | <5 | TBD |
| **Spurious microwave leakage shift,** $\delta\nu_{ML2}/\nu_0$ | <0.001 | <5 | TBD |
| **Cold collision shift,** $\delta\nu_{CC}/\nu_0$ | -0.6 | <5 | <0.006 |
| **Light shift,** $\delta\nu_{LS}/\nu_0$ | 0.02 | <1 | <0.001 |
| **Background gas collisional shift,** $\delta\nu_{BGC}/\nu_0$ | TBD | TBD | TBD |
| **Total** | 2 366.3 | 85 | 1.1 |

*Tab. 1 Preliminary accuracy budget of MuClock 00.*

### C. Position phase gradient shift

Microwave phase gradients are expected inside the cavity. The phase difference between the two Ramsey pulses also translates into a frequency shift [7-8]. The atom cloud fills a quite large volume of the cavity and atoms explore areas with potential phase gradients. As the phase of the microwave field varies spatially in the cavity, a phase is imprinted onto the atoms depending on their position as they move in the cavity due to free fall or thermal expansion.

This frequency shift can be evaluated by convolving the measured atom distribution and its free fall with the microwave phase profile obtained from finite-element simulations.

## V. Conclusion

To conclude, the collaboration between Exail and LNE-SYRTE allowed to progress on the accuracy assessment of a commercial cold-atom Rb clock. MuClock 00 was compared with the LNE-SYRTE's local frequency reference, demonstrating a long-term stability of $\sigma_{\delta\nu} = 1.0 \times 10^{-15}$ after 14 days and an absolute frequency difference of $\delta\nu = -2.0 \times 10^{-14}$. We identified three of the main effects limiting the MuClock's accuracy at current level of $u = 8.5 \times 10^{-14}$: namely the Ramsey pulling, the microwave phase transients and the spatial phase gradients). This preliminary accuracy budget is still under evaluation within the Qu-Test project with an expected overall accuracy below $u{\sim}3 \times 10^{-14}$ in the coming months.

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