Towards an accuracy budget of cold-atom-based commercial microwave clocks

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We present results of commercial microwave clocks developed by Exail Quantum Systems (formerly Muquans). The MuClocks are cold-atom-based turnkey products dedicated to continuous long-term operation. A frequency stability of 1×10^{-15} over more than a month has been demonstrated on several set-ups, competing with the frequency drift ($\sim1\times10^{-16}$/day) of the best masers[1]. Recent stability evaluations are presented in Fig. 1 showing for the best clock a long-term frequency stability of 7×10^{-16} over two weeks and for the longest run $\sim2\times10^{-15}$ over two months.

The MuClocks are built around a copper cavity used as integrating sphere to cool around 10^7 atoms by an isotropic light field to sub-Doppler temperatures. The free-falling atoms are interrogated in a Ramsey sequence with microwave pulses resonant with the copper cavity and separated by T_R = 40 ms. The atoms in the $|F = 2\rangle$ state are detected by absorption of a vertical laser beam. Using atom recapture, the cycle repetition rate is between 5 and 10 Hz.

In this contribution, we will present a preliminary accuracy budget, the targeted product accuracy being in the 5×10^{-15} range. Control and evaluation of the known frequency biases is on-going. Several frequency shifts have already been quantified: the Quadratic Zeeman shift, the cavity pulling including its asymmetry from nearby cavity resonances, microwave phase transients and the Ramsey pulling. A highly accurate setup measuring microwave phase transients with a resolution of 5 µrad has been developed and employed. The in-depth study of the atom distribution in this unusual cooling scheme has allowed to better estimate certain frequency shifts.

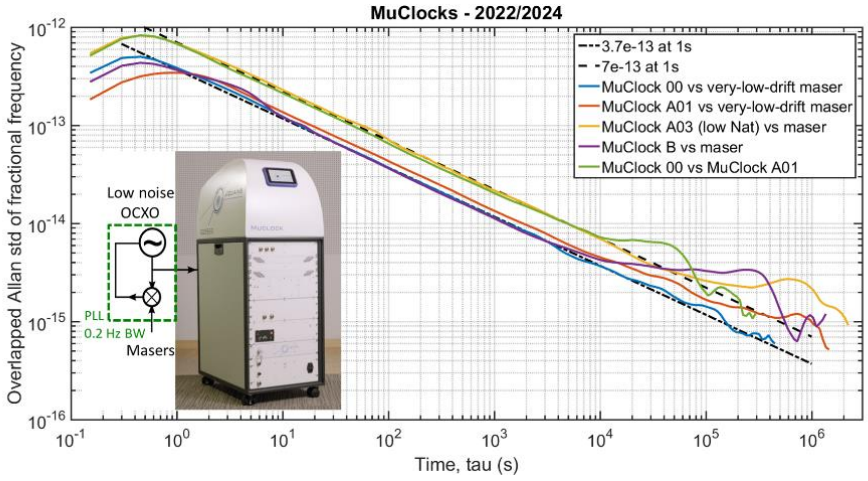

Fig. 1: Allan deviation of the fractional frequency instability of several MuClocks. Inset: MuClocks' local oscillators are locked to masers in these measurements, except for the MuClock *vs* MuClock run in green.

[1] B. Pelle, L. Archambault, B. Desruelle and A. Landragin, "Cold-atom-based Commercial Microwave Clocks at 1×10−15 Relative Instability Over More than One Month," *2022 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, Paris, France, 2022.