Laser locking to the $^{199}$Hg $^1S_0 - ^3P_0$ clock transition with $5.4 \times 10^{-15}/\sqrt{\tau}$ fractional frequency instability

J. J. McFerran,1,* D. V. Magalhães,2 C. Mandache,1 J. Millo,1 W. Zhang,1 Y. Le Coq,1 G. Santarelli,1 and S. Bize,1

LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 Avenue de l’Observatoire, 75014 Paris, France
2Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, Brazil

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With $^{199}$Hg atoms confined in an optical lattice trap in the Lamb-Dicke regime, we obtain a spectral line at 265.6 nm in which the full-width at half-maximum is $\lesssim 15$ Hz. Here we lock an ultrastable laser to this ultranarrow $^1S_0 - ^3P_0$ clock transition and achieve a fractional frequency stability of $5.4 \times 10^{-15}/\sqrt{\tau}$ for $\tau \leq 400$ s. The highly stable laser light used for the atom probing is derived from a 1062.6 nm fiber laser locked to an ultrastable optical cavity that exhibits a mean drift rate of $-0.6 \times 10^{-17}$ s$^{-1}$ ($-16.9$ mHz s$^{-1}$ at 282 THz) over a five month period. A comparison between two such lasers locked to independent optical cavities shows a flicker noise limited fractional frequency instability of $4 \times 10^{-16}$ per cavity.

Optical atomic frequency references are making significant advances in terms of accuracy [1–5] and stability [6–8] across a range of atomic species, which is important for continued investigations into a potential redefinition of the SI second, and into possible variations of fundamental constants [9]. It also motivates research into establishing low-noise frequency links between various atomic clocks over distant Earth locations via optical fibers [10, 11] and space [12, 13]. In previous work we established the potential of the $(6s^2)^1S_0 - (6s6p^2)^3P_0$ clock transition in $^{199}$Hg as a high-accuracy atomic frequency reference [14]. All the associated frequency measurements to date have relied on line-center determinations from spectral measurements. Here we lock a probe laser to the $^{199}$Hg clock transition for the first time and deduce the fractional frequency stability, $\sigma_p(\tau)$: demonstrating a $\tau^{-1/2}$ dependence typical of atomic clocks. With $\sigma_p(\tau)$ integrating down to few times $10^{-16}$ within several hundred seconds, accuracies in the $10^{-17}$ range are foreseeable in forthcoming work. We also present $\sigma_p(\tau)$ measurements between two fused-silica mirror based high-finesse optical cavities, one of which is used for the $^{199}$Hg spectroscopy, demonstrating a flicker noise floor of $4 \times 10^{-16}$ per cavity.

Many components of the $^{199}$Hg experiment have been described previously [15, 16], so we only highlight a few elements below. Atoms are confined in a vertically oriented optical lattice loaded from a single stage magneto-optical trap. Once trapped and with the MOT fields off, we apply a Rabi light pulse at the $^1S_0 \leftrightarrow ^3P_0$ transition frequency. At present we rely solely on ground state detection. There are $(2-3) \times 10^4$ atoms trapped in the lattice from which a spectral line with $\sim 11$ Hz full-width at half-maximum can be generated [13].

The source for the cooling light is a thin-disk Yb:YAG laser that is wavelength tuned using a birefringence filter and a temperature controlled etalon to 1014.902 nm. This light is frequency quadrupled through two resonant nonlinear optical cavities, the first producing $\sim 3.5$ W of 507.4 nm light and the second $\sim 70$ mW of 253.7 nm UV light. A challenging aspect of the mercury clock experiment is to produce a sufficiently deep optical lattice trap. The lower atomic polarizability of Hg in comparison to Sr and Yb implies that at least ten times more optical power is required to produce the same lattice depth. The lattice light generation begins with $\sim 900$ mW of Ti:sapphire laser light that is frequency doubled in a resonant doubling cavity to produce 160 mW of 362.570 nm light, near the magic wavelength, $\lambda_m$. The value of $\lambda_m$ has previously been determined to within 3 ppm [13]. Two spherical mirrors with radius of curvature equal to 250 mm and reflectivity of 99.5% at 360 nm form the lattice build up cavity. Here we produce $6.5 (\pm 0.7)$ W of intracavity circulating power. The waist of the cavity with $w_0(\epsilon^{-2}) = 120 \mu$m coincides with the MOT atom cloud (the atom cloud can be displaced to optimize overlap with the lattice light) and the $\epsilon^{-2}$ radius of the MOT atom cloud is $\sim 110 \mu$m prior to trap loading. Here we produce a lattice depth of 22 times the associated recoil energy, $E_R$, ($\sim 8 \mu$K).

The light for probing the clock transition at 265.6 nm

![Fig. 1. Frequency and drift-rate record of a fiber laser at 1062.6 nm locked to an ultrastable cavity with a 10 cm length ULE spacer and fused silica mirrors, recorded against the $^{199}$Hg clock transition. The mean drift rate is $-16.9$ mHz s$^{-1}$ ($-6.0 \times 10^{-17}$ s$^{-1}$).](image-url)
commences with a cavity-stabilized fiber laser at 1062.6 nm that is frequency quadrupled through two resonant cavities is presented in [17]. Despite the very low drift rate exhibited by the USL we find it accommodates slow lengthening over time, presumably due to creep in the optical cavity spacer (ULE), which is orientated vertically. The excursion seen at the end of the record is due to an abnormal temperature variation in the laboratory. (ii) The drift rate is determined by comparisons with the $^{199}$Hg clock transition. There are two characteristics of note. (i) The absolute drift rate rarely rises above 30 mHz s$^{-1}$; the mean for the data in Fig. 1(b) is $-16.9$ mHz s$^{-1}$, or in fractional frequency terms $6.0 \times 10^{-17}$ s$^{-1}$. The excursion seen at the end of the record is due to an abnormal temperature variation in the laboratory. (ii) The drift rate is rarely positive, indicating that the cavity length is slowly lengthening over time, presumably due to creep in the optical cavity spacer (ULE), which is orientated vertically.

To generate adequate power in the UV for the probe, about 400 $\mu$W of ultrastable laser (USL) light is used to injection lock a 250 mW distributed feedback semiconductor laser before carrying out the frequency quadrupling. Information regarding the frequency doubling resonant cavities is presented in [17]. Despite the very low drift rate exhibited by the USL we find it accommodating to implement a drift cancellation scheme where a digital synthesizer is used to compensate the frequency drift of the probe light interacting with the atoms. The scheme is illustrated in Fig. 2. Both the light reaching the atoms and the light received by a frequency comb experience the same drift cancellation (with a factor of 4 difference). The 1062.6 nm laser light is delivered to the main Hg table and the frequency comb by way of the optical cavity spacer (ULE), which is orientated vertically.

The cycle time is 1.46 s, of which the MOT loading time $T_c = 1.46$ s. The trace was averaged over $N = 4$ scans. The Rabi angle for the line fit is $1.3 \pi$ rad. From this data, we can estimate the cycle to cycle noise in the measurement of the transition probability to be $\sigma_{\delta P} = 0.1$, which is $\sqrt{N} = 2$ times larger than apparent in Fig. 3(b) due to the averaging. Using the relationship,

$$\sigma_y(\tau) = \frac{1}{\nu_{\text{Hg}}} \frac{\sigma_{\delta P}}{\Delta f} \sqrt{\frac{T_c}{\tau}} \quad (1)$$

where $dP/d\nu$ is the maximum slope of the resonance, we can estimate the achievable fractional frequency stability, $\sigma_y(\tau)$, when locking to the $^{199}$Hg line spectrum. With $dP/d\nu = 0.02$ Hz$^{-1}$, we find $\sigma_y(\tau) \sim 5.3 \times 10^{-15}/\sqrt{\tau}$.

By sampling the clock transition at the points of half-maxima (either side of center) we derive a correction signal that is delivered to AOM 3 (and AOM 1) of Fig. 2 so that the frequency of the probe light becomes locked to the $^{199}$Hg clock transition. In order to evaluate the clock instability, the comb derived IR frequency is averaged and only the long term drift is taken into account (since the noise of the microwave reference in the comb measurements dominates that of the USL). This way the short term fluctuations of the measured $\nu_{\text{probe}}$ are due solely to that imposed by the atomic resonance. An example of $\nu_{\text{probe}}$ versus time is shown in Fig. 4(a), where the frequency is offset by that reported in [13]. The cycle time is $1.46$ s, of which the MOT loading time
is 1.32 s. The fractional frequency instability for this data (Fig. 4 b), filled circles) exhibits \( \sigma_\nu(\tau) = 5.4 \times 10^{-15}/\sqrt{\tau} \) out to 400 s, in good agreement with the instability predicted above.

For comparison, an assessment of \( \sigma_\nu(\tau) \) between two USL cavities is shown by the hollow squares of Fig. 4 b). One USL is that described above with \( \lambda = 1062.6 \) nm, while the other is a similar design, but has the ULE spacer horizontally orientated [15]. A separate Yb:fiber laser is locked to each cavity, having a frequency difference of \( \sim 1 \) GHz (the USLs are in separate laboratories). The minimum fractional instability obtained is \( 5.7 \times 10^{-16} \). Assuming equal contributions from the cavities, each exhibits a \( \sigma_\nu(\tau) = 4.0 \times 10^{-16} \) flicker floor. We also show the limit to \( \sigma_\nu(\tau) \) set by the Dick-effect for our present probe sequence. The calculation uses an estimation of the USL noise based on the measurement of Fig. 4 b) (hollow squares) along with earlier recorded USL vs H-maser data [17]. The limiting stability is \( 8.1 \times 10^{-15}/\sqrt{\tau} \), lying well below that shown for the \( ^{199}\text{Hg} \) resonance lock. These results show that further gains in the \( ^{199}\text{Hg} \)-locked laser frequency stability can be made by improving the S/N of the clock transition. At present the contrast of the clock resonance is \( \sim 15\% \). With a deeper lattice trap (e.g. with a reduced beam waist) and the use of atom number normalization methods we expect to increase the contrast and S/N such that the very low Dick-effect instability limitation is reached.

To conclude, we have demonstrated a fractional frequency instability of \( 5.4 \times 10^{-15}/\sqrt{\tau} \) for a 265 nm laser light locked to the clock transition of \( ^{199}\text{Hg} \), and a short term instability of \( 5.7 \times 10^{-16} \) between two lasers locked to separate 10 cm long cavities. One optical cavity exhibited a mean drift rate of \( 6.0 \times 10^{-17} \) s\(^{-1} \) over a six month period; one of the lowest reported for optical cavities at RT. We also show the first laser lock to a spectral line of \( ^{199}\text{Hg} \) (Fig. 4 b), filled circles) exhibits \( \sigma_\nu = 10^6 \nu_{\text{Hg}} \) clock transition derived from \( \nu_{\text{Hg}} \) (open squares) comparison between two ultrastable optical cavities and (solid line) Dick-effect limited instability.

![Fig. 4. (a) (Color online) \(^{199}\text{Hg} \) frequency (offset by \( \nu_{\text{Hg}} = 1128575290808162.0 \) Hz) versus time. (b) Fractional frequency instability plot: (filled circles) ultrastable laser locked to the \(^{199}\text{Hg} \) clock transition derived from \( \nu_{\text{Hg}} \) (open squares) comparison between two ultrastable optical cavities and (solid line) Dick-effect limited instability.](image-url)

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