Time-variation measurement of fundamental constant using femtosecond laser frequency combs

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Over the past half-century, atomic frequency standards with ever-greater stability and accuracy have played a prominent role in many experiments and disciplines, from navigation and communications to precision metrology and spectroscopy. For example, microwave atomic clocks orbiting the earth now permit position identification to the order of centimeters anywhere on the globe while standards from the microwave to the optical have produced some of the most stringent tests of our fundamental concepts and theories of nature. Furthermore, highly accurate, absolute frequency measurements of several microwave and optical frequency standards have sensitively probed for a possible time dependence of fundamental constants [1-3].

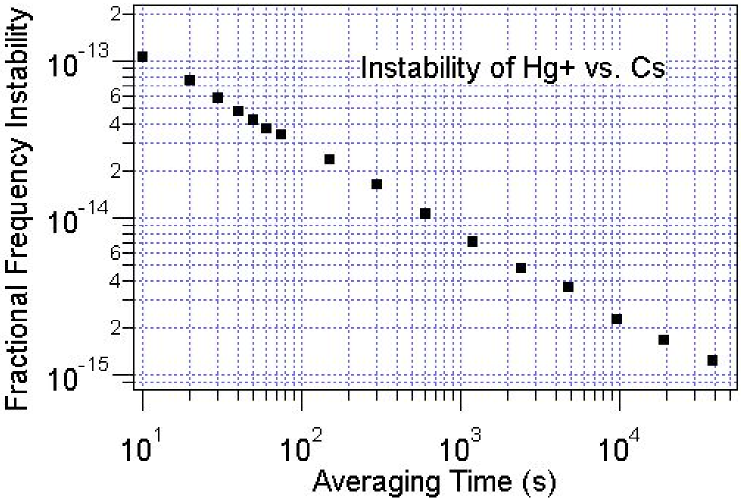

Fig. 1: Relative fractional frequency instability of the ^{199}Hg$^+$ optical frequency standard vs. the primary ^{133}Cs fountain standard NIST-F1.

In this summary, we report our recent measurement of the absolute frequency of the ^{199}Hg$^+$ single-ion electric-quadrupole clock transition in terms of the SI second as realized by the NIST-F1 cesium fountain clock. The relative fractional frequency instability of the comparison of the two standards reaches 1×10^{-15} at $\sim 4 \times 10^4$ s (Fig. 1), which is the "white-noise" stability floor expected for the NIST-F1 cesium fountain for the operating conditions of this measurement. We phase lock a Ti:sapphire-based femtosecond laser frequency combs [4] to the local oscillator of the Hg+ standard at 532 THz. This optical frequency is divided down by the FLFC to yield an optical pulse train that is photodetected to provide a ~1 GHz electronic signal, which is then compared to another 1 GHz signal synthesized from a hydrogen maser. The same hydrogen maser is employed in the synthesis of the 9.2 GHz microwaves that probe the cesium atoms in the fountain. Simultaneous recordings of the maser-synthesized signals versus those derived from the two atomic standards permits the reduction of the long-term fluctuations of the maser in this comparison.

In Fig. 2, the absolute frequency measurements of the mercury standard that have been made over the past 4.5 years are plotted. The preliminary value of the weighted mean of all data gives ν_{Hg} = 1 064 721 609 899 145.2 (1.2) Hz. The frequency of the Hg^+ standard for each measurement has been corrected by 0.55 Hz to account for the different gravitational red shifts resulting from an elevation differential of about 5 m between the two standards. A linear fit to the data weighted by the total uncertainty for each measurement gives a line whose slope is +0.56 ± 1.0 Hz/yr. As before, this can be interpreted as constraining a possible fractional variation of $g_{Cs}(m_e/m_p)\alpha^{6.0}$ [5] at the same level. If we assume that any change in this quantity is due to the $\alpha^{6.0}$ factor, then, when our data analysis is completed, we are able to posit a more stringent limit to a possible temporal variation of the fine-structure constant α.

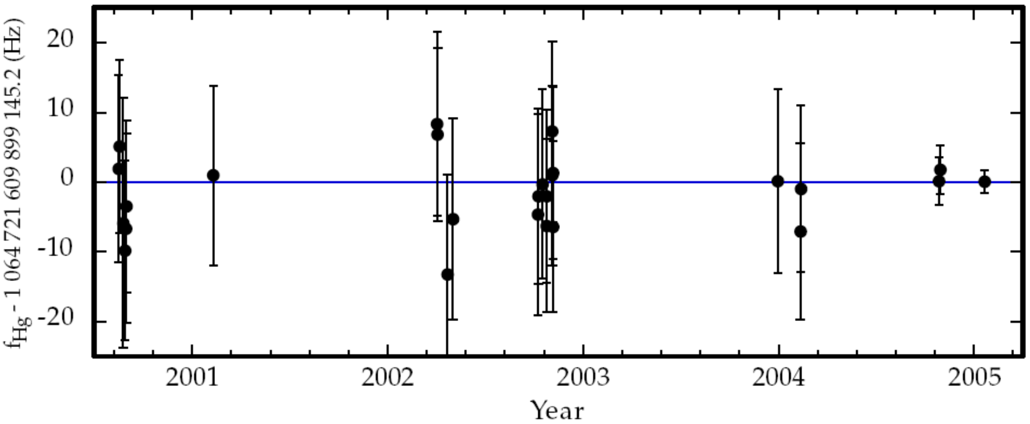

Fig. 2: Absolute frequency measurements of the $^{199}Hg^+$ electric-quadrupole transition. The mean value of each measurement is offset by the weighted mean of all data. The total uncertainty of each measurement is indicated by the vertical error bars.

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In this summary, we report our most recent measurement of the absolute frequency ν_{Hg} of the $5d^{10}6s\ ^2S_{1/2}\,(F=0) \leftrightarrow 5d^9 6s^2\ ^2D_{5/2}\,(F=2,\ m_F=0)$ electric-quadrupole transition in a single $^{199}Hg^+$ ion. For this measurement, ν_{Hg} was directly compared to the primary ^{133}Cs fountain standard NIST-F1 using an optical frequency comb based on a self-referenced femtosecond laser [6]. The preliminary estimate of the absolute frequency is 1 064 721 609 899 145.3 (1.5) Hz. The fractional frequency inaccuracy of the measurement of the optical clock frequency is 1.5×10^{-15}, which is the square root of the quadrature sum of the uncertainties due to Cs (0.53×10^{-15}), Hg^+ (1.1×10^{-15}), and to the type-A measurement uncertainty (0.9×10^{-15}). The relative fractional frequency instability of the comparison of the two standards reaches 1×10^{-15} at $\sim 4 \times 10^4$ s (Fig. 1), which is the “white-noise” stability floor expected for the NIST-F1 cesium fountain for the operating conditions of this measurement [7].

In Tables 1 and 2, we list the systematic shifts with the largest fractional uncertainties for the ^{133}Cs fountain standard and the $^{199}Hg^+$ optical standard respectively. The optical-to-microwave conversion with the frequency comb generated by the femtosecond laser has a fractional frequency uncertainty smaller than 1×10^{-16} [10]. The fractional frequency uncertainty of NIST-F1 is dominated by spin-exchange and blackbody frequency shifts, whereas the largest fractional frequency uncertainties for the optical standard are associated with the quadrupole shift [11], the second-order Doppler shift, and the ac Stark shift. The latter two shifts are caused by residual motion (termed “micromotion”) of the ion at the rf-drive frequency for the trap [12]. Reasonable care was taken to eliminate the micromotion, such that the fractional frequency shifts from these two terms were less than 1×10^{-16}. The quadrupole shift was fractionally no larger than 1×10^{-15}. In future runs, we hope to reduce the fractional frequency uncertainties of all of the systematic shifts to the order of 1×10^{-18}.

Table 1: Error budget for the ^{133}Cs fountain standard, NIST-F1

Effect	Fractional Frequency Correction ($\times 10^{-15}$)	Fractional Frequency Uncertainty ($\times 10^{-15}$)
Spin Exchange Shift	1.48	0.41

Second-order Zeeman Shift	+35.99	0.10
Blackbody Shift	-19.31	0.26
Microwave Effects (Leakage & Distributed Cavity Phase)	0.0	0.14

Table 2: Error budget for the $^{199}\mathrm{Hg}^{+}$ optical frequency standard

Effect	Fractional Frequency Correction $(\times 10^{-15})$	Fractional Frequency Uncertainty $(\times 10^{-15})$
Quadrupole Shift	0.0	1.0
Second-order Zeeman Shift	+1.18	0.04
Gravitational Redshift (relative to NIST-F1)	+0.52	0.01
Micromotion Shifts (2nd-order Doppler & AC Stark)	0.0	<0.1