Record Atomic Frequency Standard Stability With Mercury in a Linear Ion Trap

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Microwave optical double-resonance spectroscopy measurements of the ground-state $^2S_{1/2}(\mathrm{F} = 0, \mathrm{m_F} = 0)$ *to* $^2S_{1/2}(\mathrm{F} = 1, \mathrm{m_F} = 0)$ *hyperfine transition of* ^{199}*Hg ions are used to control a local oscillator. With interrogation times of 8 s, a shot noise limited stability of* $\sigma_{\mathrm{y}}(\tau) = 6.5 \times 10^{-14}/\tau^{1/2}$ *is achieved. Comparisons made for 33 and 24 days between two linear ion trap research frequency standards (LITS), LITS-1 and LITS-2, demonstrate a frequency stability currently exceeding other standards for averaging times between 10,000 and* 10^6 *s. LITS-2 was also compared to a cavity-tuned hydrogen maser for 146 days, with the long-term differential drift measured to be* $(2.1 \pm 0.8) \times 10^{-16}$*/day. Initial measurements using a new two-segment extended linear ion trap indicate a stability of* $\sigma_y(\tau) = 5.6 \times 10^{-14}/\tau^{1/2}$ *and reduced sensitivity to long-term environmental perturbations.*

I. Introduction

All radio-frequency references in the Deep Space Network (DSN) are derived from very stable atomic frequency standards. The 40.5-GHz ground-state hyperfine transition of ^{199}Hg ions [1] provides the basis for a new generation of high-performance standards [2,4–6]. In this article, the first stability comparisons longer than 10^6 s between two $^{199}\mathrm{Hg}^+$ linear ion trap frequency standards (LITS) are presented. These measurements were performed between the first two laboratory research standards, LITS-1 and LITS-2, which had little regulation and isolation from environmental perturbations.

Initial stability measurements of an improved standard, LITS-3, and results from a two-segment variation, the extended linear ion trap (LITE) [13], are also reported. This new ion trap should provide even better long-term stability and a significant reduction in size, weight, and cost.

II. The Mercury Linear Ion Trap Standard (LITS)

Ions confined in a trap allow for long interrogation times and high atomic line Q. Continuous operation is practical using a ^{202}Hg lamp to generate 194.2-nm radiation for atomic state selection [1] and helium buffer gas for ion cooling [2]. The large 40.5-GHz $^2S_{1/2}(F = 0, m_F = 0)$ to $^2S_{1/2}(F = 1, m_F = 0)$ ground-state hyperfine transition (Fig. 1) is less susceptible to magnetic and Doppler shifts than are lighter atoms. The linear ion trap [3] provides a way to increase the detected fluorescence signal-to noise ratio (SNR) without increasing the second-order Doppler shift. Fluorescence is detected with two optical

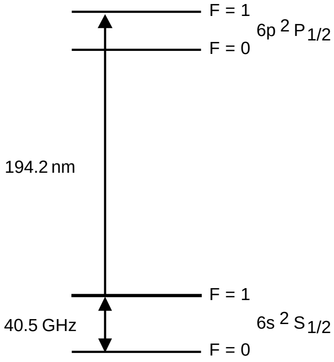

Fig. 1. Simplified ^{199}Hg$^+$ energy level diagram.

systems orthogonal to the lamp input direction. Approximately 150,000 photons are detected in 1.6 s with from 15 to 20 percent of the photons coming from the ions. The hyperfine transition is interrogated using Ramsey successive oscillatory fields with two 0.4 s microwave pulses separated by an interrogation time, T_R, ranging from 1 to 30 s.

The expected fractional frequency of the passive frequency standard can be expressed as

$$\sigma_y(\tau) = \frac{2}{\pi}\,\frac{1}{Q}\,\frac{N}{S}\left(\frac{T_c}{\tau}\right)^{1/2} \tag{1}$$

where $Q = f_0/\Delta f$, Δf is the central Ramsey fringe width, f_0 is 40.5 GHz, S is the peak ion fluorescence, B is the background light, $N = (S/2 + B)^{1/2}$, T_c is the cycle time, and τ is the averaging interval. Presently, the largest frequency shifts are due to the applied magnetic field, the second-order Doppler shift, and a helium pressure shift. Typical operating parameters and environmental sensitivity of the research standards LITS-1 and LITS-2 have been reported upon previously [5].

The ^{199}Hg$^+$ clock transition has been previously measured with an uncertainty of 2.5×10^{-13} [2], and improvements to 10^{-16} may be possible with single laser cooled ions [8]. There are good indications that 10^{-14} accuracy is possible with the linear ion trap standards [5,7,10]. The accuracy and long-term stability is directly related to the size of the frequency offsets and the degree to which they are known, measured, and controlled. Magnetic and second-order Doppler shifts can be measured from Zeeman transitions and motional sidebands [9,10]. For mercury in an ion trap, frequency offsets typically are smaller than for primary cesium beam standards, which currently achieve accuracy of 10^{-14}.

III. Stability Measurements Between Two Trapped-Ion Standards

The original research standards, LITS-1 and LITS-2, have no direct regulation of ion number, and three large magnetic shields provide a shielding factor of 800. Measurements were performed in a thermal environment controlled to 0.1 deg C. Both standards operated with an interrogation time of 16 s (total cycle time = 20 s) and a performance of from 7 to $8 \times 10^{-14}/\tau^{1/2}$. For stability comparisons, each ion trap steers a separate hydrogen maser (H-maser) receiver [6]. Figure 2 shows a 6-day measurement between LITS-2 and LITS-1. A stability of 5×10^{-16} is achieved at 100,000 s with good statistics. LITS-2 is also compared to an active hydrogen maser, SAO-26,[1] of the type currently used in the DSN, which typically drifts at 3×10^{-15}/day.

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[1] Smithsonian Astrophysical Observatory, Cambridge, Massachusetts.

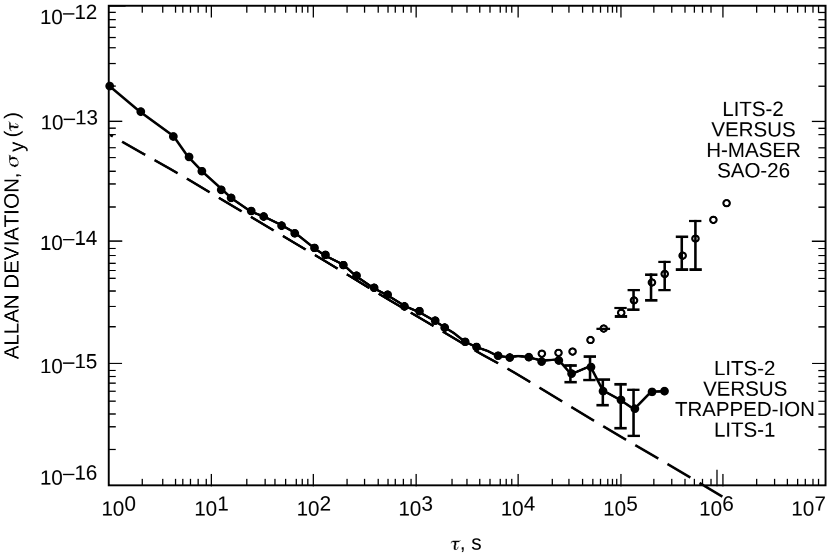

Fig. 2. Fractional frequency stability between LITS-1 and LITS-2.

Presently, only two comparisons have been performed for longer durations. Figure 3 shows stability measurements of LITS-2 between August 12, 1994, and January 5, 1995, against the hydrogen maser SAO-26 and a cavity-tuned hydrogen maser, STSC-ST1.[2] Cavity tuning improves hydrogen maser long-term stability by an order of magnitude, though short-term stability is degraded. The average differential drift between LITS-2 and the STSC-ST1 maser over the 146-day measurement interval was $(2.1 \pm 0.8) \times 10^{-16}$/day. The measured long-term stability of the hydrogen masers shown in Fig. 3 is characteristic of the technology [11,12]. LITS-2 was also compared to LITS-1 for 33 days (August 1994–September 1994) and 24 days (December 1994–January 1995), respectively. The 33-day measurement (shown with squares) occurred with recurring magnetic perturbations to LITS-1, partly explaining the additional noise as compared with the 24-day measurement (shown with stars). The 24-day measurement was performed over a quieter holiday season.

Even though little effort was spent regulating and isolating LITS-1 and LITS-2 from environmental perturbations, the first ion trap stability measurements already exceed both cavity-tuned H-maser and time-scale stability for averaging times from 10,000 to at least 10^6 s [12]. To verify that no large common drift existed between the two LITS, the STSC-ST1 maser was also referenced to the National Institute of Standards and Technology Coordinated Universal Time (NIST-UTC) via Global Positioning System (GPS) common view measurements during the 146-day period that LITS-2 and the STSC-ST1 maser were compared. The average drift between STSC-ST1 and NIST-UTC was $\approx 2 \times 10^{-16}$/day.

IV. Initial Stability Measurements With LITS-3

A recently completed standard (LITS-3) operates continuously and has improved trapping potential and electron loading current stability. Five magnetic shields increase the longitudinal shielding factor from 800 to 17,000. The applied magnetic field has been lowered from 80 to 40 mG, reducing the shielded sensitivity to ambient magnetic fluctuations to 1×10^{-17}/mG. An SNR of 75 is obtained with an interrogation time of 8 s (cycle time = 12 s). Figure 4 shows a 5-day measurement of the new standard LITS-3 against an active H-maser. The measured short-term Allan deviation of $\sigma_y(\tau) = 6.5 \times 10^{-14}/\tau^{1/2}$

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[2] Sigma Tau Standards Corporation, Tuscaloosa, Alabama.

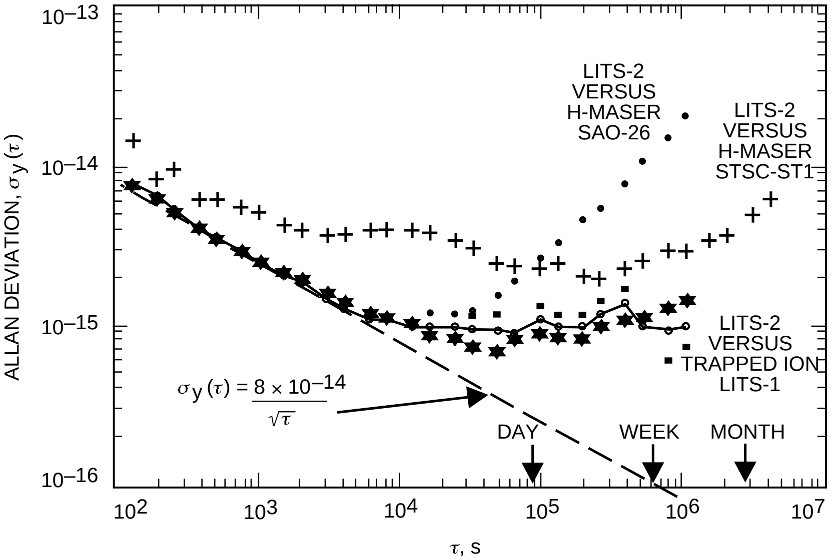

Fig. 3. Fractional frequency stability of the research Hg^+ standard LITS-2 compared with the ion trap standard LITS-1 for 24 and 33 days, a cavity-tuned hydrogen maser for 146 days, and an active hydrogen maser.

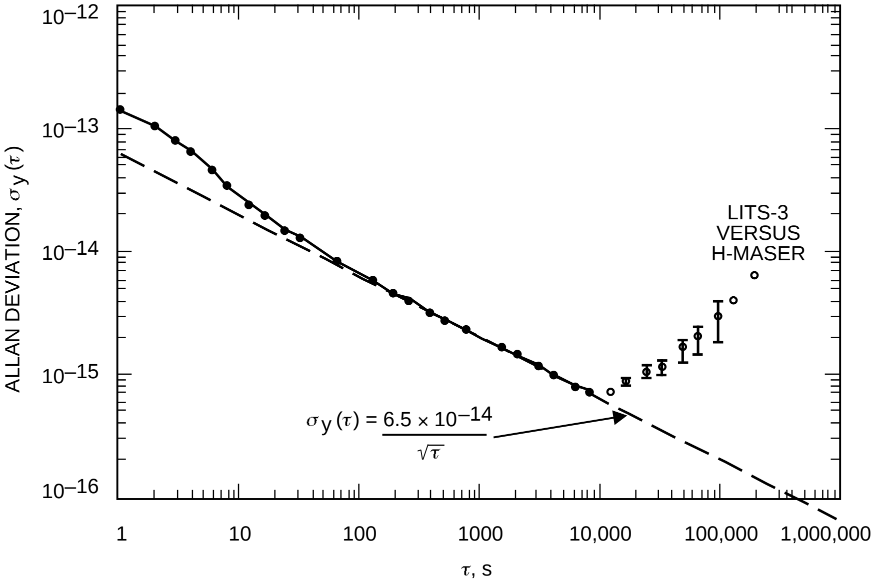

Fig. 4. Five-day stability measurement of the LITS-3 compared with the hydrogen maser SAO-26. The stability measurement past 10,000 s is limited by the H-maser reference standard.

is accomplished with an 8-s microwave interrogation time, a factor of two shorter than is used in LITS-1 and LITS-2. This performance is in excellent agreement with that predicted using Eq. (1). The stability floor is better than 7×10^{-16} at 10,000 s. For averaging times longer than 10,000 s, the measurement is limited by drift in the reference hydrogen maser. Measurements against other mercury trapped-ion standards, or other high-stability standards as they become available, are needed to better characterize the stability floor.

V. Initial Results With the Extended Linear Ion Trap (LITE)

A two-segment extended variation of the linear ion trap, Fig. 5(a), was developed to provide practical and performance advantages over the current standards [13]. The distinguishing feature is separation of the ion-loading and optical-pumping region from the microwave interrogation region. Ions are moved back and forth between the two regions with DC potentials. Only the microwave interrogation region needs to be magnetically shielded. In addition to being much smaller, the lamp and detection optics are accessible without removing the magnetic shields. The magnetic field can be made more homogeneous, allowing operation at lower fields. Ions can be loaded during the interrogation time, allowing good SNR and improved short-term performance. A version with three segments would allow dual-trap operation with no local oscillator degradation [14].

Figure 5(b) shows the ≈40.5-GHz Ramsey signal obtained using the LITE trap and an interrogation time of 11.1 s. The observed frequency is the magnetic shielded frequency, although the optical pumping/state selection occurred when the ions were unshielded from the Earth's field [equivalent to ≈7 Hz higher in Fig. 5(b)]. With the SNR observed in Fig. 5(b) and a total cycle time of 16 s, Eq. (1) predicts an expected performance of $\sigma_y(\tau) = 5.6 \times 10^{-14}/\tau^{1/2}$. Adding a second light collection system would provide another factor of $2^{1/2}$ in the SNR, enabling a performance of $\sigma_y(\tau) = 4 \times 10^{-14}/\tau^{1/2}$.

When the microwave region is longer than the fluorescence region, the sensitivity to possible fluctuation/drift of the confined ion number will be reduced without compromising SNR. The second-order Doppler shift in the linear trap is proportional to the linear ion density, N/L [3]:

$$\left(\frac{\Delta f}{f}\right)_{2nd\ Doppler} = -\left(\frac{q^2}{8\pi\epsilon_0 mc^2}\right)\frac{N}{L} \tag{2}$$

where N is the confined ion number and L is the length of the trap. From Eq. (2), the sensitivity of the first LITE trap to ion number fluctuations should be reduced by a factor of 5 from the previous LITS. The length of the microwave interrogation region can be made shorter for applications where size and mass must be minimized, or much longer when accuracy and long-term stability are desired.

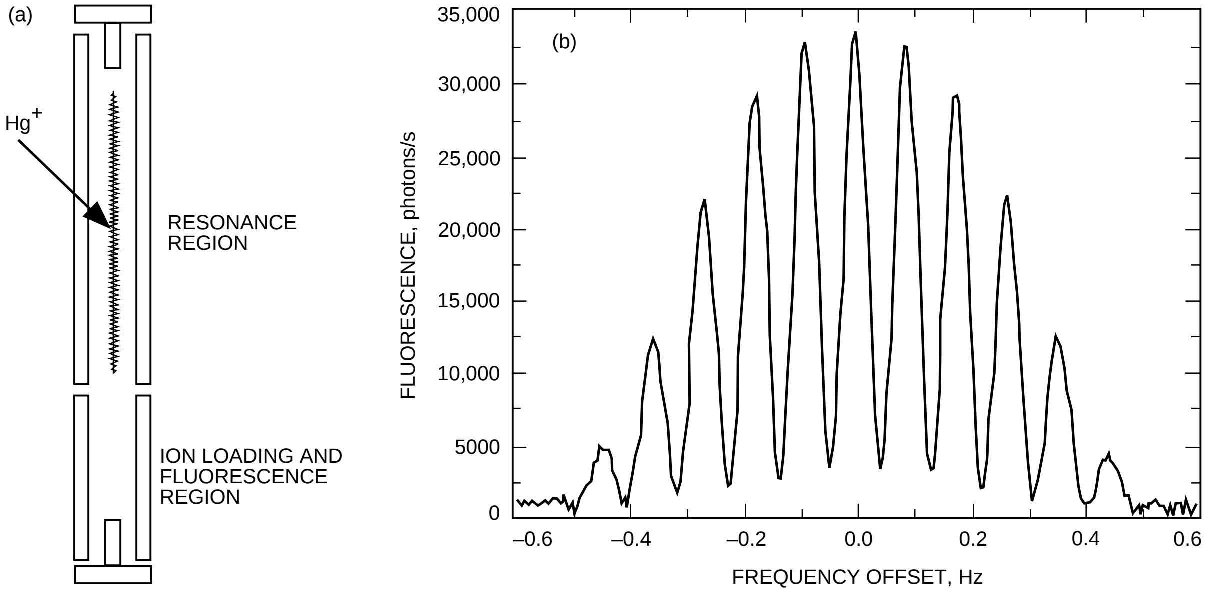

Fig. 5. The extended linear ion trap: (a) conceptual diagram and (b) Ramsey fringes from a 11.1 s interrogation cycle in the new LITE trap.

VI. Summary

The measured stability of the ground-state hyperfine transition of ^{199}Hg ions in LITS-2 currently exceeds other frequency standards for averaging times from 10,000 to at least 10^6 s. Stability comparisons for 33 and 24 days were made between two linear ion trap research standards, LITS-1 and LITS-2, with the flicker floor observed at or below 7×10^{-16}. LITS-2 also was compared to a cavity-tuned H-maser, STSC-ST1, for 146 days, with the long-term differential drift measured to be $(2.1 \pm 0.8) \times 10^{-16}$/day. These first-generation, linear trapped-ion frequency comparisons were obtained with no active regulation of ion number, a thermal regulation of 0.1 deg C, and a magnetic shielding factor of 800. A recently completed standard (LITS-3) has better magnetic shielding and control electronics for continuous operation and improved long-term stability. With an interrogation time of 8 s, a short-term stability of $\sigma_y(\tau) = 6.5 \times 10^{-14}/\tau^{1/2}$ is obtained. The measured stability of this new standard is 7×10^{-16} at 10,000 s.

Initial signal-to-noise measurements using a new extended linear ion trap (LITE) indicate a stability of $\sigma_y(\tau) = 5.6 \times 10^{-14}/\tau^{1/2}$. Operating with reduced linear ion densities and lower magnetic fields should enable further improvements in long-term stability.

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