Improved short-term stability of optical frequency standards: approaching 1 Hz in 1 s with the Ca standard at 657 nm

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For a neutral ^{40}Ca-based optical frequency standard we report a fractional frequency instability of 4×10^{-15} in 1 s, which represents a fivefold improvement over existing atomic frequency standards. Using the technique of optical Bordé–Ramsey spectroscopy with a sample of 10^7 trapped atoms, we have resolved linewidths as narrow as 200 Hz (FWHM). With colder atoms this system could potentially achieve an instability as low as 2×10^{-16} in 1 s. Such low instabilities are important for frequency standards and precision tests of fundamental physics.

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One of the great improvements promised by the advent of optical atomic frequency standards is a substantial increase in frequency stability over that of state-of-the-art microwave standards. Over the past few years the stability (for short averaging times) of several optical standards has reached or surpassed the best of their microwave counterparts.[1–7] We have now reduced the amplitude and frequency noise levels for our neutral ^{40}Ca-based standard, leading to a fractional frequency instability of 4×10^{-15} in 1 s, which represents a fivefold improvement over the best reported atomic or ionic frequency standards.

Improvements in frequency standards come primarily on three fronts: short-term stability, reproducibility, and, ultimately, accuracy. In this Letter we focus on the short-term stability of an atomic frequency standard based on laser-cooled and trapped Ca atoms, a system that has the potential for excellent performance in all three aspects. Because of the limited signal-to-noise ratio (S/N) in probing atoms, the stability for short averaging times ($\tau \leq 1$ s) of an atomic frequency standard is often orders of magnitude worse than the ultimate accuracy. Thus one is forced to average for hours or days to make a measurement at the accuracy of the standard. Improved short-term stability will reduce this averaging time, permitting rapid evaluation of the standard's performance and faster convergence to improved accuracy. Additionally, precision measurements and tests of fundamental physics will benefit from shorter averaging times because of reduced sensitivity to environmental fluctuations, which typically diverge at low frequencies.

Based on the success of the Cs fountain[8] and trapped ion standards, it is clear that future atomic standards will use cold atoms and that we want to move to optical (rather than microwave) frequencies, assuming that we can do this without incurring additional performance-limiting constraints. The advantage of optical standards can be seen in the basic relation for the fractional frequency instability, $\sigma = \Delta\nu/(\nu_0 \times \mathrm{S/N})$, where $\Delta\nu$ and ν_0 are the linewidth and the center frequency of the measured atomic transition, respectively. Optical standards based on ions confined to the Lamb–Dicke regime have the significant advantages of narrow linewidth and reduced systematic errors resulting from reduced atomic motion, whereas standards based on trapped neutral atoms benefit from a large number of atoms, which should provide a high S/N.

We have chosen to work with the 657-nm $^1S_0(m = 0) \rightarrow {}^3P_1(m = 0)$ intercombination line of neutral Ca because of its narrow linewidth (400 Hz), insensitivity to external parameters, and accessibility with diode lasers.[9] Moreover, the resonance line at 423 nm (35-MHz linewidth) works well for laser cooling, which provides the long interaction times required for subkilohertz spectroscopy and reduces systematic effects for the optical standard. In achieving high stability, the challenge has been to resolve the 657-nm clock transition with high resolution (<1 kHz) while achieving a good S/N (>500 in 1 s).

Our apparatus has been described in detail elsewhere,[3] so we summarize only its basic features, with an emphasis on those that are most relevant to the improved stability. We generate 40 mW of blue light for trapping and cooling by doubling the frequency of an 846-nm extended-cavity diode laser–amplifier system. We have constructed a simple Ca magneto-optic trap, which is loaded by a short (13-cm) thermal atomic beam. In 10 ms we can load $\sim 10^7$ atoms into the trap, with a residual atomic temperature of 2 mK. The relatively high temperatures achieved for laser-cooled alkaline earth atoms by use of the resonance lines are a result of their $J = 0$ ground states, which permit only simple Doppler cooling.

The probe-laser system at 657 nm also consists of an extended-cavity diode laser–amplifier combination and provides 38 mW of spatially filtered intensity-stabilized light. To achieve the frequency stability required for subkilohertz spectroscopy we lock the laser frequency tightly to a narrow Fabry–Perot cavity fringe. We derive the error signal by use of the Pound–Drever–Hall technique,[10] and by feeding corrections back to the laser current, we have achieved a servo bandwidth >3 MHz. With the ULE (ultralow-expansion) cavity as a reference, this stabilized laser then serves as the local oscillator for the Ca spectroscopy. Since reference-cavity fluctuations lead to laser frequency noise, which can limit S/N for the spectroscopy, it is critical to isolate the cavity from environmental perturbations. To this

end the cavity is placed in a vacuum can (pressure $<10^{-5}$ Pa), which rests on our optical table. The vacuum can is enclosed in an aluminum box lined with lead foam, which is used for acoustic damping. Active servo control of the air legs levels the table and dampens vibrations. The frequency of the probe light is swept across (or locked to) the Ca resonance with a synthesizer-controlled double-passed acousto-optic modulator, which provides a frequency offset between the laser and the cavity. We can also send a ramp to the synthesizer to cancel thermal drifts of the reference cavity, which for these measurements was without active thermal control.

We have made two significant changes to our stabilization system, which have enabled us to reduce the frequency noise by a factor of 5. First, we have replaced our previous cavity (50-kHz linewidth) with one that is five times narrower, reducing our sensitivity to residual amplitude modulation, line noise, and dc offsets. Second, we have improved the isolation of the cavity by placing it on an Invar V block with inset Viton spacers and then resting the V block on its own Viton spacer. Inclusion of the spacers removed virtually all frequency noise at Fourier frequencies above 100 Hz, with a vast majority of the noise residing below 10 Hz.

To excite the clock transition we use the technique of optical Ramsey spectroscopy with four traveling-wave pulses (as first suggested by Bordé[11]), which utilizes most of the atoms even at high resolution. To improve the S/N further we use a shelving detection scheme with a near-resonant blue pulse (10-μs duration) after the 657-nm excitation to measure the degree of excitation before significant decay occurs.[3] Since we can cycle several hundred photons per atom on the blue transition, our S/N is increased (by a factor of 20) over that of red-fluorescence collection from the $^3P_1$ excited state. Because of the large number of atoms and some residual technical noise, our detection sensitivity is not yet at the atom-projection-noise limit.[8,12] Nonetheless, with the recent addition of an acousto-optic modulator to stabilize the blue intensity level ($\sim$0.1% fluctuations), we attained a fourfold reduction in the amplitude noise of our detection system, pushing it below the limit set by the frequency noise on the red laser.

To generate the spectroscopic signals we measure the fluorescence induced by the blue pulse with a gated integrator and hold this value until the next 6-ms measurement cycle is completed. We generate line shapes by continuously cycling the measurement sequence while sweeping the 657-nm laser frequency. This enables us to view real-time 0.5-s sweeps on an oscilloscope and make rapid adjustments to the spectrometer. At our present S/N we are able to see Bordé–Ramsey fringes for single sweeps at linewidths as narrow as 380 Hz (FWHM). To reduce sensitivity to low-frequency fluctuations in the signal and generate an error signal that is suitable for locking, we modulate the red probe-laser frequency at 75 Hz (limited by our cycle time) with a square-wave amplitude equal to the fringe width. With this modulation present we found it redundant to include a normalization detection pulse before red excitation as described in Ref. 3, although the normalization pulse was still present for the data shown in Fig. 1. After demodulation, the signal is fed to a digital oscilloscope with which we can analyze and (or) average the line shape. Figure 1 shows fringes at a resolution equal to the 400-Hz natural linewidth. In fact, this spectroscopic technique permits the generation of subnatural linewidths (albeit with decreased fringe contrast), allowing us to see fringe linewidths as narrow as 200 Hz. At higher resolution the S/N degrades significantly because of spontaneous emission, thermal expansion of the atoms, and laser noise resulting from reference-cavity fluctuations.

A rigorous evaluation of the stability of our Ca standard would involve comparison of our system with another stable system. Unfortunately, this will have to wait for an optical synthesis system that is under development,[13] which will permit measurements relative to Cs and the 282-nm clock transition[7] in Hg^+. We can, however, put some upper limits on the instability at short times by comparing the Ca signal with out 657-nm reference cavity. This comparison is, of course, sensitive to fluctuations that are due to both the Ca spectrometer and the reference cavity (including relevant lock parameters). Nonetheless, we can still make some inferences about the noise sources and estimate the minimum system stability. We perform the comparison by simply parking the laser on the side of a demodulated Ca fringe and measuring the fluctuations. We then convert these voltage fluctuations to the frequency domain, using a dc-coupled FM port on a frequency synthesizer, which serves as a voltage-to-frequency ($V \rightarrow f$) converter. We experimentally set the $V \rightarrow f$ scaling (with 5% uncertainty), using calibrated laser frequency steps.

Figure 2(a) shows a time series of frequency fluctuations measured with a fringe width of 960 Hz, although fringe widths from 600 to 1200 Hz give similar results. The most informative statistic for evaluating frequency fluctuations is the Allan deviation, which we have measured for the system under a variety of conditions. For times <1 s the deviations are very repeatable, with fluctuations that average down at a rate of approximately $\tau^{-1/2}$ [see Fig. 2(b)] but then flatten

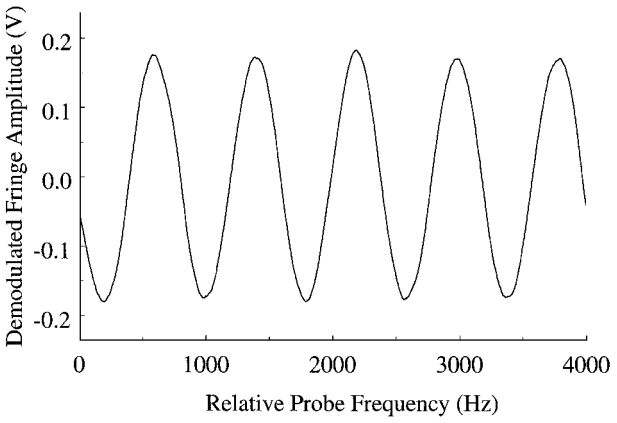

Fig. 1. Optical Bordé–Ramsey fringes taken at the natural linewidth of 400 Hz (FWHM). The total data averaging time was 1 min.

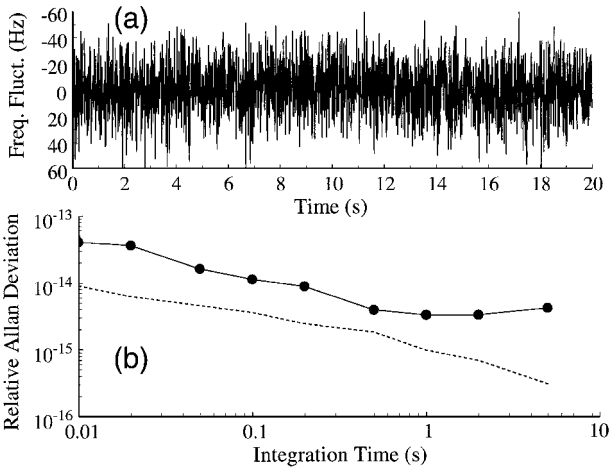

Fig. 2. (a) Frequency fluctuations (for an optical frequency of ~456 THz) between the Ca signal and the Fabry–Perot reference cavity. (b) Allan deviation for fluctuations shown in (a) (the filled circles represent data points). The contribution to the Allan deviation by the noise on the blue readout system is shown by the dashed curve.

out at 4×10^{-15} (or <2 Hz for the 456-THz optical frequency). To see the flat section ($\tau > 1$ s) it is necessary to cancel the drift associated with the reference cavity to less than 2 Hz/s, which we do by feeding a ramp to the laser frequency control. Any residual drift can then be removed by a linear fit to the data. Unfortunately, for this type of measurement the cavity drift is not usually constant over several minutes, so scans longer than this are almost certainly dominated by cavity instability. The flattening out around 1 s is most likely due to cavity fluctuations as well, but fluctuations in parameters associated with the spectroscopy of the atoms (e.g., magnetic fields, laser beam alignment) cannot be ruled out at the hertz level. Since the fluctuations are approximately three to four times larger on the side of the fringe than on top, we conclude that we are still limited by frequency noise, most likely owing to imperfect vibration isolation of the optical cavity. By measuring the noise on the blue detection system without red excitation, we confirm its lesser contribution to the Allan deviation [see Fig. 2(b)].

Reducing cavity-length fluctuations is clearly essential to improve our system's short-term stability. Improving long-term cavity stability with active thermal control will be useful for evaluation of the Ca system but is not critical to the performance of the operating standard, since locking to the atomic transition should suppress cavity drifts. One of the real advantages of the Ca system is its short measurement cycle (5–10 ms), which enables us to correct the laser frequency quickly (10–20-Hz servo bandwidth), thus relaxing the long-term cavity-stability requirements.

Our value of 4×10^{-15} at 1 s is to our knowledge the lowest Allan deviation reported to date for an atomic or ionic frequency standard, but this is not a fundamental limit, and we anticipate improvements from Ca and other optical references. With our present system, improved cavity isolation should enable us to reach an instability of 10^{-15} at 1 s. Furthermore, we project that with a trapped-atom temperature of 10 μK it should be possible to reach $<2 \times 10^{-16}$ at 1 s. To reach these projected instability levels and attain good accuracy for the standard, we must have excellent control over spectroscopic parameters such as stray fields, beam alignment, and atom-cloud drift velocity. The issue of accuracy with the Ca system has been addressed elsewhere[2] (with potential inaccuracy estimates of $\approx 10^{-15}$) and is under investigation by us well. In fact, with excellent stability nearly at hand, the next great challenge for the optical standards community will be to demonstrate inaccuracies of $<10^{-15}$, in order to become competitive with the cold-atom microwave standards.

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