# Optical Frequency Stabilization at the $10^{-16}$ Fractional Level Utilizing Ramsey-Borde Atom Interferometry


J. Olson[§], R. Fox, T. Fortier, C. W. Oates, and A. D. Ludlow[†]

Time and Frequency Division

National Institute of Standards and Technology

Boulder, CO,USA

jbo@nist.gov[§], [†]ludlow@boulder.nist.gov



***Abstract*— We demonstrate laser frequency stabilization at the $10^{-16}$ fractional frequency level in one second through spectroscopy on a 650 ˚C calcium atomic beam. The calcium beam is interrogated with a cavity stabilized 657 nm laser arranged in a Ramsey-Borde configuration. A second laser at 431 nm reads off the final atomic state populations while allowing for high signal-to-noise. Limitations of this method are being explored and, and, based on current noise analysis, there is potential to achieve fractional frequency stabilities in the $10^{-17}$ range or below.**



***Index Terms* — *Measurement, precision measurements, optical clock, optical frequency standard, atomic clock, calcium, stabilized laser, calcium, Ramsey, Bordé***


## I. Introduction

Modern laser stabilization typically relies on high-Q Fabry-Perot cavities, to which a laser's optical mode is locked. Using this method with carefully designed, well isolated cavities has yielded short-term laser frequency stabilities in the $10^{-17}$ range, with applications ranging from low-noise-microwave generation, dark matter detection, optical clocks, and quantum computing. However, cavity stabilization at these levels is often limited by fundamental thermal-mechanical fluctuations in the cavity itself. Thus, a variety of non-traditional methods are being explored to improve laser stabilization beyond anticipated cavity limitations or meet cavity limitations in a more accessibly fashion. Here, we communicate one such approach used to achieve high performance in a relatively simple apparatus: high resolution Ramsey-Bordé interferometry on a thermal beam of atomic calcium.

## II. Ramsey-Bordé and Calcium

Ramsey-Borde (RB) interferometry [1] can be a means for Doppler-free spectroscopy with high resolution and large signal-to-noise. Furthermore, the atom-laser interactions can be tuned to address broad atomic-velocity distributions, allowing a simple thermal beam to be efficiently interrogated rather than a cooled or trapped atomic sample. RB interferometry has been used on calcium atoms in a variety of configurations for decades, beginning in the late 1970's (e.g. [2-5]). As is typical, we employ RB spectroscopy on the 657 nm $^1S_0$-$^3P_1$ intercombination line with a natural linewidth of ~400 Hz.

To create the four laser-atom interactions fundamental to RB interferometry, we generate a travelling wave laser configuration, as in Fig.1, through which a beam of calcium atoms pass. The geometry is determined by a monolithic ultra-low-expansion (ULE) glass assembly with optically contacted mirrors. The ULE structure was chosen to space the first and fourth interactions far from the inner two interaction zones. By maximizing the beam spacing, we create long Ramsey free-evolution times, allowing us to achieve interference fringes with ~1.5 kHz spectral linewidth.

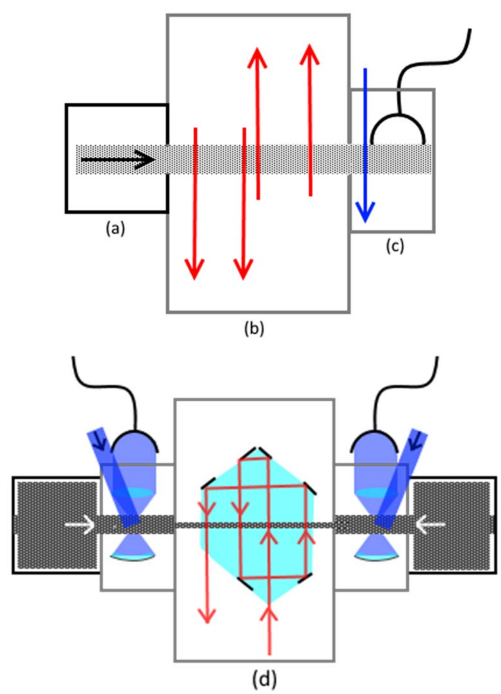


**Fig. 1** Schematic of experimental basis. (a) An oven and apertures generate a well-collimated calcium atomic beam. (b) The atomic beam is traversed in four zones by two anti-parallel pairs of parallel laser beams. (c) The excited state fluoresce is observed. Signal-to-noise is improved through a fast cycling transition from the excited state. (d) Actual implementation of dual oven system with counterpropagating atomic beams and in-vacuum optical path.

Detection of RB fringes in calcium has typically been done through either collection of spontaneous decay from the $^3P_1$ excited state or a second 423 nm transition to fluorescence the $^1S_0$ ground state population. However, we have instead taken advantage of a doubly-excited $^3P_0$ state of calcium obtainable from $^3P_1$ via a mixed polarization 431 nm laser source. This broad 40 MHz transition allows interrogation of the RB excited state population with orders of magnitude improvement in signal-to-noise over the spontaneous decay collection method.

## III. LASER STABILIZATION

In order to realize our RB fringes, the 657 nm interrogation laser is first cavity stabilized to a compact Fabry-Perot cavity, yielding an initial fractional frequency stability of ~$3x10^{-15}$ at one second. The laser is then intensity and phase stabilized before interacting with the atomic beams.

To avoid residual first-order Doppler shifts and relative phase drift of our calcium interference fringes, we use two counterpropagating and overlapping atomic beams. RB interrogation is interleaved between the two atomic beam fringes resonances. As the residual Doppler shifts and relative phases experienced by the two atomic beams are equal and opposite, stabilizing our interrogation laser frequency to both atomic beams can suppress these effects.

## IV. RESULTS

Thus far, we have stabilized our 657 nm laser to ~$2x10^{-16}$ at 10 seconds and 3.5 $x10^{-16}$ at one second. Frequency stability was also promising over much longer interrogation periods. Instabilities at or below $5x10^{-16}$ were seen for time periods between 1 and 1000 seconds. Over a 20 hour data set, removing the expected impact of measured ambient temperature fluctuations revealed fractional frequency instabilities remaining in the $10^{-16}$ regime for the duration.

## V. CONCLUSIONS

We have achieved unprecedented laser stability from a thermal-atom system that is competitive with ultra-stable Fabry-Perot cavities. We are working toward improving both our short- and long-term fractional frequency stabilities in hopes of achieving shot-noise-limited performance, which is still at least another order of magnitude beyond our current results.

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