

Narrow-linewidth Brillouin laser for a two-photon rubidium frequency standard

Kyle W. Martin[✉] and River Beard

AV Incorporated, 1300 Britt Street Albuquerque, New Mexico 87123, USA

Andrei Isichenko[✉], Kaikai Liu, and Daniel J. Blumenthal[✉]

Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106, USA

Seth E. Erickson[✉], Kaleb Campbell[✉], and Sean Krzyzewski^{*}

Space Vehicles Directorate, Air Force Research Laboratory, Kirtland Air Force Base, Albuquerque, New Mexico 87117, USA



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High-precision, portable, and deployable frequency standards are required for modern navigation and communication technologies. Optical frequency standards are attractive for their improved stability over their microwave counterparts; however, increased complexities have anchored them in the laboratory. Sacrificing the sensitivity of the most stable optical clocks has led to the recent development of deployable and portable optical frequency standards, leveraging hot atomic or molecular vapor. The short-term limit for a majority of previous reports on two-photon rubidium standards is either the shot-noise or intermodulation limit hindering the 1 s fractional frequency stability to around 1×10^{-13} . The answer for the shot-noise limit is to increase optical power and collected fluorescence, while the intermodulation limit solution requires improvements in laser linewidth, stimulated Brillouin scattering (SBS) lasers are known to reduce frequency noise, suppressing noise of the pump laser. We investigate an optical frequency standard based on the two-photon transition in ^{87}Rb probed with a narrow photonic integrated circuit SBS laser with a quality factor over 130 million and instantaneous linewidth < 10 Hz. The use of a narrow clock laser coupled with operating at higher optical intensities yielded clock instabilities of 2×10^{-14} at 1 s, currently the best reported short-term stability for a two-photon rubidium optical frequency standard.

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I. INTRODUCTION

Modern communication, navigation, and sensing systems rely on portable clocks and oscillators to provide necessary stable frequency and phase sources [1]. While crystal and MEMS oscillators meet a vast majority of timing needs, more precise and robust applications require atomic clocks. Microwave clocks based on rubidium and cesium are currently the most popular technology fulfilling this need [1,2]. These atomic microwave standards have provided robust and stable phase and frequency sources and have well-understood frequency shifts and drifts [3]. Nonetheless, emerging technologies such as femtosecond two-way optical time transfer [4–9] and high frequency

distributed antenna systems [10,11] require even more stable low size, weight, and power (SWaP) frequency standards. These emerging technologies, coupled with improvements in existing communication, navigation, and sensing technologies, add significant value to portable atomic frequency standards with superior timing stability.

Current state-of-the-art single ion [12–14] and optical lattice clocks [15–17] yield excellent results in controlled laboratory environments. Efforts to bring these more advanced optical lattice and ion clocks from a laboratory environment into the field are an active area of research [18–23]. However, single ion and optical lattice clocks have yet to make an impact with more stringent requirements of SWaP, robustness, and autonomy necessary for widespread communication, navigation, and sensing. Selective tradeoffs need to be made for advanced deployable clocks to be used in a more widespread manner.

In order to meet the stringent demands for deployable clocks, research teams have often elected to simplify the state-of-the-art optical clocks to prioritize certain advancements in frequency stabilization. Several efforts have

^{*}Contact author: qst@afrl.af.mil

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maintained a fundamental microwave clock frequency while adding lasers for state preparation [24] or for laser cooling to reduce Doppler and collisional shifts [25]. Nevertheless, these microwave standards still lack the higher short-term stability of their optical counterparts. Portable optical cavities have also garnered interest in recent years [26,27]; while generally superior in performance at short timescales, they lack an atomic reference and suffer from long-term frequency drifts. The use of hot atomic [28] or molecular vapors [29] has had recent success operating outside the laboratory in a relevant SWaP envelope. These hot atomic or molecular optical clocks retain high stability at short timescales (leveraging stable optical oscillators) while simultaneously benefiting from long-term stability of the probed atomic or molecular energy transitions.

We investigate the optical rubidium atomic frequency standard leveraging the $5S_{1/2}(F=2) \rightarrow 5D_{5/2}(F=4)$ transition in ^{87}Rb and detecting fluorescence decay along the $6P_{3/2} \rightarrow 5S_{1/2}$ [30–41]. This transition has several advantages as the required clock laser can be generated through second-harmonic generation of telecom C-band laser systems, the fluorescence is easy to distinguish from the clock laser at 778 nm, and the relatively high excitation rate for a two-photon system. However, the short-term clock performance is generally limited by either photon shot-noise or laser frequency noise in the form of intermodulation limit [31]. In this article, we demonstrate an improvement on both of the short-term limitations by using high intensity to suppress photon shot-noise and a photonic integrated circuit stimulated Brillouin scattering (SBS) laser to reduce the intermodulation limit.

II. SHORT-TERM CLOCK LIMITS

A recent review article of the $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transition in Rb [31] concluded that for the majority of reports, the short-term limit is either photon shot noise or laser frequency noise in the form of the intermodulation limit.

A. Photon shot-noise limit

The statistical uncertainty involved in detecting photons gives rise to a fundamental limitation of any photodetector known as photon shot noise. The photon shot noise sets the limit for Refs. [36–43]. A frequency standard whose Allan deviation [44] is limited by photon shot-noise limit can be written as [45],

$$\sigma_y^{(\text{SN})} = \frac{1}{\nu_0} \sqrt{\frac{S_f}{2\tau}}, \quad (1)$$

where

$$S_f = \left(\frac{g}{p}\right)^2 \frac{S_v}{2}. \quad (2)$$

τ is the averaging time, ν_0 is the clock transition frequency, g is the mixer gain, p is the error signal slope, and S_v and S_f are the measured voltage and frequency noise, respectively, in the detector bandwidth. Reduction of shot noise can be achieved by improving the error signal slope, p . In fluorescence-based frequency standards, p can be increased by improving collection efficiency, although this has an upper limit. The collection efficiency for this work and Lemke *et al.* [38] is approximately 7%–8% of the fluoresced photons, with the currently best reported number Perrella of 15% [46], which appears to be the practical upper limit. Alternatively, amplified probe light intensity can increase p , consequently, ac-Stark effects may limit long-term performance [43].

B. Intermodulation limit

All oscillators have broadband noise, consequently, this noise bypasses filtering and demodulation in error signal generation. In continuous wave frequency modulation, this is known as the intermodulation limit for the oscillator (the Dick effect for pulsed systems). The intermodulation limit sets the short-term performance for Refs. [33,34], restricting fractional frequency performance to 3×10^{-12} at 1 s. The intermodulation limit is derived in Ref. [47] and can be written as follows:

$$\sigma_y^{(\text{IM})} = \frac{(S_y^{(\text{LO})}[2f_m])^{1/2}}{2\sqrt{\tau}}, \quad (3)$$

where $S_y^{(\text{LO})}[2f_m]$ is the noise spectral density at twice the modulation frequency. Ahern *et al.* [42] noted that for multiphoton processes, the frequency noise on each photon needs to be included. Consequently, the total state intermodulation limit needs to sum over the frequency noise of each excitation photon; this was overlooked in Martin *et al.* [43]. Correlated noise from two sources (e_1 and e_2) adds as follows:

$$e_y = \sqrt{e_1^2 + e_2^2 + 2ce_1e_2}, \quad (4)$$

where $-1 \leq c \leq 1$ is the correlation parameter. The intermodulation limit for a degenerate two-photon excitation ($c = 1$) can now be rewritten as follows:

$$\sigma_y^{(\text{IM})} = \frac{(S_y^{(\text{LO})}[2f_m])^{1/2}}{\sqrt{\tau}}. \quad (5)$$

Typically, laser noise is inversely proportional to offset frequency. Consequently, the intermodulation limit can be suppressed by increasing the modulation frequency,

although the atomic lifetime sets an upper limit for this noise reduction technique for fluorescence detection; for two-photon rubidium, this upper limit is approximately 2 MHz. Ultimately, for frequency standards operating in the intermodulation limit a higher quality, narrower laser is required.

In some instances, both the photon shot noise and intermodulation limits are sufficiently small and the short-term limit is driven by environmental instabilities. This is the case in Perrella *et al.* [48], where clock laser alignment limited performance. Reducing the short-term limit of the two-photon Rb frequency standard requires reduction of both the intermodulation and shot-noise limits as well as careful consideration to all environmental instabilities.

III. MATERIALS AND METHODS

The experimental apparatus evolved from the system described in Ref. [38]. However, in order to suppress both intermodulation and shot noise, the experiment operates at increased optical intensities relative to [38], while reducing noise spectral density by stabilizing the clock laser to a SBS resonator [49]. The SBS laser resonator is fabricated on an ultra-low-loss silicon nitride platform. The waveguide dimensions are 40 nm in thickness and 11 μm in width, designed to achieve low propagation loss and a low Brillouin lasing threshold. The radius of the resonator is 11.787 μm , ensuring the resonances match the Stokes shift [50]. The SBS laser has reduced laser phase noise in the high-frequency offset region (< 100 kHz), propagation loss of 0.1 dB/m, and the loaded quality factor (Q) is 130 million at 1550 nm. These SBS lasers can reach a low lasing threshold of 14 mW and a sub-Hz fundamental linewidth [49]. Stabilizing the SBS output to the $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transition in ^{87}Rb similar to Isichenko *et al.* [51] will improve SBS stability at timescales greater than 1 s.

Two separate experiments with different clock lasers were performed: one utilizing a narrow 1556 nm RIO Planex external cavity diode laser (ECDL) with a measured instantaneous linewidth 1.1(15) kHz producing 20 mW of optical power, the second experiment stabilizes the same ECDL to a microresonator generating SBS, see Fig. 1. To produce SBS, light from the ECDL is sent through a fiber-coupled waveguide electro-optical phase modulator (EOM) driven at 22 MHz to generate frequency sidebands for Pound-Drever-Hall lock [52]. The light is then sent through a circulator to the microresonator, where the transmitted light is detected using an InGaAs photodiode. The counterpropagating SBS signal is sent back through the circulator and then to an erbium doped fiber amplifier (EDFA). After this point, the laser system for the two separate experiments is identical. Figure 1 also shows the measured decrease in frequency noise

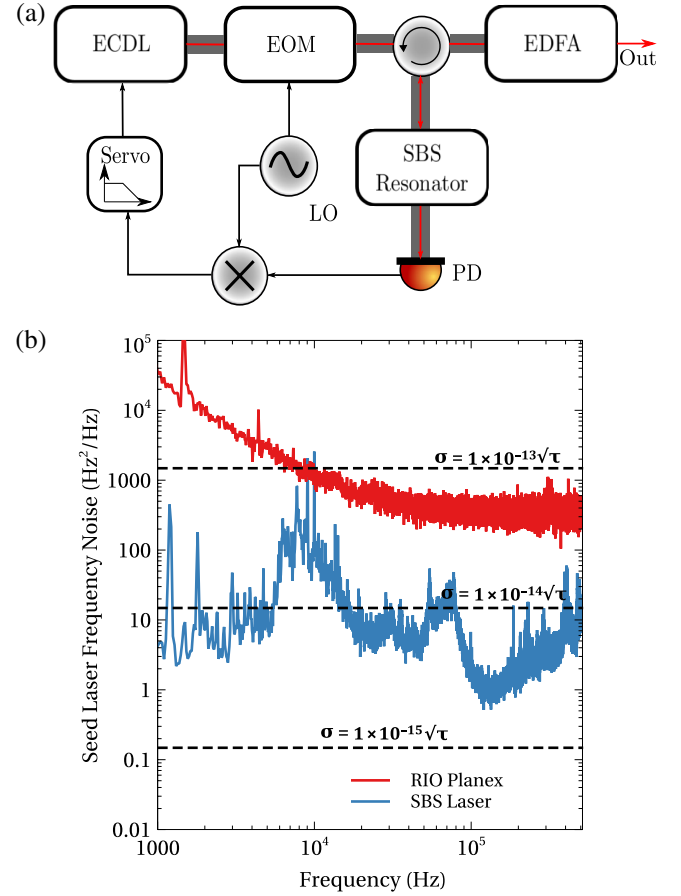


FIG. 1. (a) System diagram of the ECDL locked to an integrated silicon nitride resonator, as described in the text. The stimulated Brillouin scattering output (labeled out) is used to probe the $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transition. (b) The decrease in measured frequency noise of the SBS laser over the ECDL as measured against a stable cavity-locked laser (fractional frequency $< 3 \times 10^{-15}$ at 1 s). Horizontal lines indicating intermodulation limited clock performance are also shown. PD, photodiode; EDFA, erbium doped fiber amplifier; EOM, electro-optic modulator; ECDL, external cavity diode laser; LO, local oscillator; SBS, stimulated Brillouin scattering.

of the SBS output over the ECDL, measured directly via optical heterodyne between the seed laser and a reference cavity laser with a sub-hertz linewidth, SLS-INT-1550-200-1 [53].

Figure 2 shows the experimental diagram after seed laser generation. The laser, ECDL or SBS, is sent to a fiber-coupled acousto-optic modulator (AOM) frequency shifter, the actuator for atomic stabilization. At this point, approximately 10% of the optical power is sampled to be measured against a reference. The laser is sent through a preamplification EDFA, followed by another low residual amplitude modulation (RAM) EOM [54,55] modulated at 101 kHz, targeting the lowest phase noise of the SBS and ECDL. The light is sent through another EDFA and

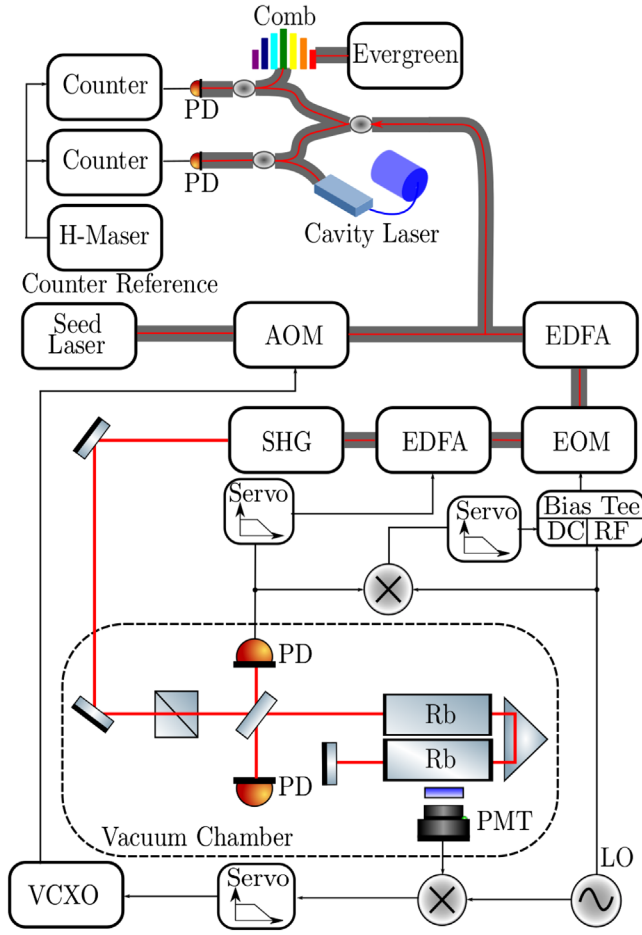


FIG. 2. System diagram of the SBS laser locked to the two-photon transition in Rb, as described in the text. The clock laser is directly compared via a heterodyne with both a cavity-stabilized laser and an optical frequency comb stabilized to a molecular iodine standard labeled Evergreen in the figure. PD, photodiode; EDFA, erbium doped fiber amplifier; EOM, electro-optic modulator; LO, local oscillator; SBS, stimulated Brillouin scattering; VCXO, voltage controlled crystal oscillator; AOM, acousto-optic modulator; SHG, second harmonic generation; PMT, photomultiplier tube.

undergoes second harmonic generation (SHG) in a PPLN waveguide producing as much as 100 mW of light at 778.1 nm.

The generated 778.1 nm light is carried by optical fiber to a vacuum chamber enclosing the Rb cell apparatus. The entire free-space portion is mounted to a temperature-controlled, water-cooled breadboard. The light is collimated to a beam with an intensity radius ($1/e^2$) of $w_0 = 1.05(2)$ mm. The free-space laser is directed through a long-pass filter to eliminate unintended third-harmonic light [56], a polarizer, and a pellicle beam splitter to sample the light for power stabilization. The beam passes through two fused silica vapor cells (length 50 mm, diameter 10 mm) connected via a 180° turning prism

and enclosed in μ -metal to reduce background magnetic fields. The cells are filled with isotopically pure ^{87}Rb and heated to 100°C using low field resistive heaters. Although previous experiments used a cat's eye retroreflector [37,38,57], a flat mirror was chosen to reduce pointing stability requirements on the collimator [43]. A large area PMT is mounted on top of the vapor cells behind a short-pass optical filter to collect the 420 nm fluorescence from the rubidium atoms with high efficiency.

The PMT output is demodulated with a temperature-stabilized analog mixer at 101 kHz to generate the error signal. An analog servo controller with dual integrators and approximately 20 kHz bandwidth stabilizes the laser frequency by steering the shift applied by the AOM to the peak of the fluorescence signal.

InGaAs photodiodes with low capacitance (< 2 nF) in photovoltaic mode detect each reflection from the pellicle beam splitter. Although the responsivity is lower for InGaAs than Si, the differential temperature responsivity coefficient for InGaAs is smaller than Si, making the detector less susceptible to thermal fluctuations. The detector response is amplified using a transimpedance amplifier (bandwidth > 1 MHz); the 778.1 nm laser power is stabilized to the forward beam pick-off adjusting the pump current of the final EDFA. Additionally, the signal from the photodiode is mixed with 101 kHz sinusoidal signal, generating an error signal used to suppress RAM by feedback to a dc bias across the EOM [55]. The second photodiode is used as a witness for both the power servo and RAM servo, used to measure how well these environmental instabilities are suppressed.

The stabilized 1556 nm seed light (10% sampled after the AOM) is then sent to be compared against two references: the SLS cavity laser and a Vector Atomic Evergreen-30 iodine frequency standard via optical heterodyne. Each heterodyne detection was measured with a frequency counter referenced to a hydrogen maser. Since the heterodyne is generated in the optical domain, the frequency counter only requires mHz level measurement stability to measure optical frequency instabilities $< 1 \times 10^{-15}$.

IV. RESULTS

Measured clock performance can be impacted by environmental variables, reference clock performance, shot noise, and intermodulation noise. Ideally, all of the environmental impacts on the frequency standard are well understood, measured, and suppressed. However, Eq. (6) sums the intermodulation, shot-noise limit, and direct measurements of remaining impacts from ac-Stark ($\sigma_y^{(\text{ac-Stark})}$), RAM ($\sigma_y^{(\text{RAM})}$), Rb-Rb collisional $\sigma_y^{(\text{Rb-Rb})}$, and the reference clock ($\sigma_y^{(\text{ref})}$), yielding a prediction of clock performance from environmental effects,

$$\begin{aligned}\sigma_y(\tau)^2 = & [\sigma_y^{(\text{IM})}(\tau)]^2 + [\sigma_y^{(\text{SN})}(\tau)]^2 + [\sigma_y^{(\text{RAM})}(\tau)]^2 \\ & + [\sigma_y^{(\text{ac-Stark})}(\tau)]^2 + [\sigma_y^{(\text{Rb-Rb})}(\tau)]^2 \\ & + [\sigma_y^{(\text{ref})}(\tau)]^2.\end{aligned}\quad (6)$$

To calculate ac-Stark-limited performance, the rear-going photodiode measurement was calibrated by converting detected voltage to optical power. This optical power measurement, free-space beam waist, and the ac-Stark transfer function found in Ref. [43] of $2.5 \times 10^{-13}/(\text{mW}/\text{mm}^2)$ are used to calculate $\sigma_y^{(\text{ac-Stark})}(\tau)$. For Rb-Rb-collision-limited clock performance, out-of-loop temperature measurements scaled by the temperature transfer function in Ref. [57] of $1.1 \times 10^{-12}/\text{K}$ are used to calculate $\sigma_y^{(\text{Rb-Rb})}(\tau)$. Additionally, prior to clock measurement, a low-frequency sinusoid was applied to the dc port of the bias tee whose output is sent to the EOM seen in Fig. 2 to determine the proper scaling of detected RAM to clock frequency and calculate RAM-limited clock performance, $\sigma_y^{(\text{RAM})}(\tau)$. Finally, shot-noise limit and intermodulation limit were calculated using Eqs. (1), (2), and (5) with the values reported in Table I. All of these clock limits are shown in Fig. 3.

The fractional frequencies of the references were measured directly in separate experiments. The stability

TABLE I. Free-space laser measured parameters alongside measurements necessary to calculate the intermodulation and shot-noise limit of a given experiment.

Shared values	
Parameter	Value
Atomic transition linewidth	476(13) kHz
Optical input power	58.4(3) mW
Mixer gain (g)	0.58(4)
Beam waist radius	1.05(2) mm
Amplifier seed: RIO planex laser	
Instantaneous linewidth	1.10(15) kHz
Error signal slope (p)	1.0(2) $\mu\text{V}/\text{Hz}$
Voltage spectral density (S_v)	$1.0(4) \times 10^{-10} \text{ V}^2/\text{Hz}$
Power spectral density ^a	373(22) Hz^2/Hz
$\sigma_y^{(\text{IM})}(\tau = 1 \text{ s})$	$5.0(2) \times 10^{-14}$
$\sigma_y^{(\text{SN})}(\tau = 1 \text{ s})$	$7.5(20) \times 10^{-15}$
Amplifier seed: SBS laser	
Instantaneous linewidth	8(2) Hz
Error signal slope (p)	1.08(3) $\mu\text{V}/\text{Hz}$
Voltage spectral density (S_v)	$3.6(2) \times 10^{-11} \text{ V}^2/\text{Hz}$
Power spectral density ^a	1.8(2) Hz^2/Hz
$\sigma_y^{(\text{IM})}(\tau = 1 \text{ s})$	$3.46(20) \times 10^{-15}$
$\sigma_y^{(\text{SN})}(\tau = 1 \text{ s})$	$4.2(3) \times 10^{-15}$

^aAt 202 kHz.

of the cavity-locked laser was measured via optical heterodyne with two independent cavity lasers of similar performance [58] and determined to be $3.5(3) \times 10^{-15}$ at 1 s with a drift of 2.5(5) kHz/day driven by the laboratory environment. The cavity laser performs well in the short term, while the Vector Atomic Evergreen-30 iodine frequency standard was used for long-term comparisons. The iodine clock was measured against the reference cavity laser using an optical heterodyne as well as compared with a second Vector Atomic Evergreen iodine standard; its stability was determined to be $3.1(1) \times 10^{-14}/\sqrt{\tau}$ for 100 s with a specified drift rate of $< 2 \text{ Hz/day}$ [59].

Figure 3 shows measured clock performance when compared with two stable references. For simplicity, only the lower of the two instabilities is shown as the measured result in Fig. 3, thereby ignoring instabilities and drifts that occur from imperfect references. Additional details of individual reference clock heterodyne measurements can be found in Fig. 4. Moreover, Eq. (6) is used to calculate the expected clock performance given environmental measurements. This calculation is also shown in Fig. 3 and is in good agreement with measured performance over short and long timescales, within a factor of 4 for the duration of the experiment.

For the ECDL clock-based system, short-term instability is set by the intermodulation limit. The heterodyne measurement between the stabilized clock laser and either the iodine frequency comb or the cavity laser system yields similar results. For this clock laser, both references are more stable than the two-photon clock at 1 s.

For the SBS clock laser, a dramatic decrease in the intermodulation limit is predicted. Additionally, a discrepancy begins to appear between the cavity and iodine heterodynes. In this case, the two-photon clock outperforms the iodine frequency standard at 1 s averaging times. However, neither the predicted shot noise nor the intermodulation limits explain the 1 s instability. The RAM of the system appears to be limiting clock performance in the short term, with measured performance $< 2\times$ worse than expected. Since there is still excess SNR, a future experiment could be planned to demodulate using the third harmonic and further reduce the impact of RAM, at the cost of SNR [38,60], or by leveraging more advanced RAM mitigation techniques [61].

At timescales beyond 100 s both clock laser choices show similar performance. The long-term stability (in this case $> 1 \times 10^5 \text{ s}$) is limited by power instability via ac-Stark shift. This could be improved with new ac-Stark mitigation techniques [62] and by using digital servos to reduce voltage set point drifts [38].

Midterm performance limitation remains a bit of a mystery. The biggest disagreement between measured and expected performance occurs around 10,000 s. Laboratory temperature was oscillating for the duration of each experiment with a period of 2000 s. This oscillating room

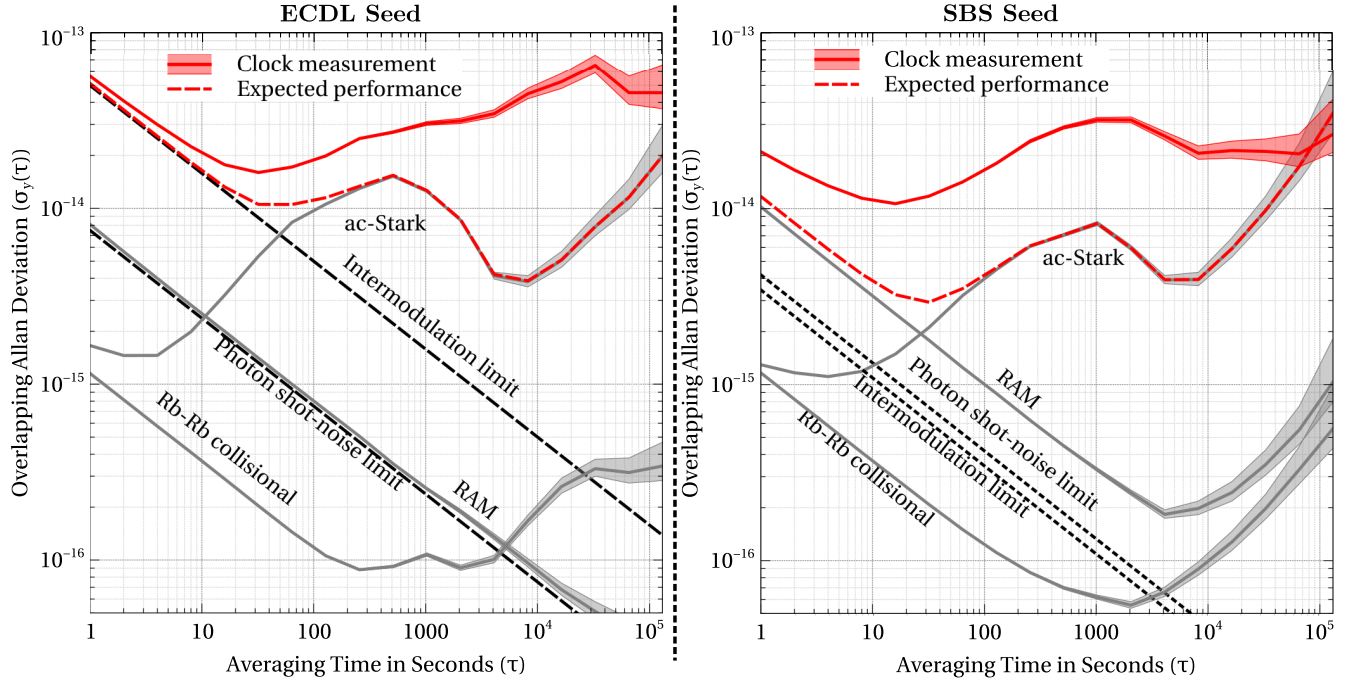


FIG. 3. Alongside the measured and expected clock performance are the measured environmentally driven instabilities: Rb-Rb collisional, RAM, and ac-Stark all properly scaled to account for the impact on clock stability.

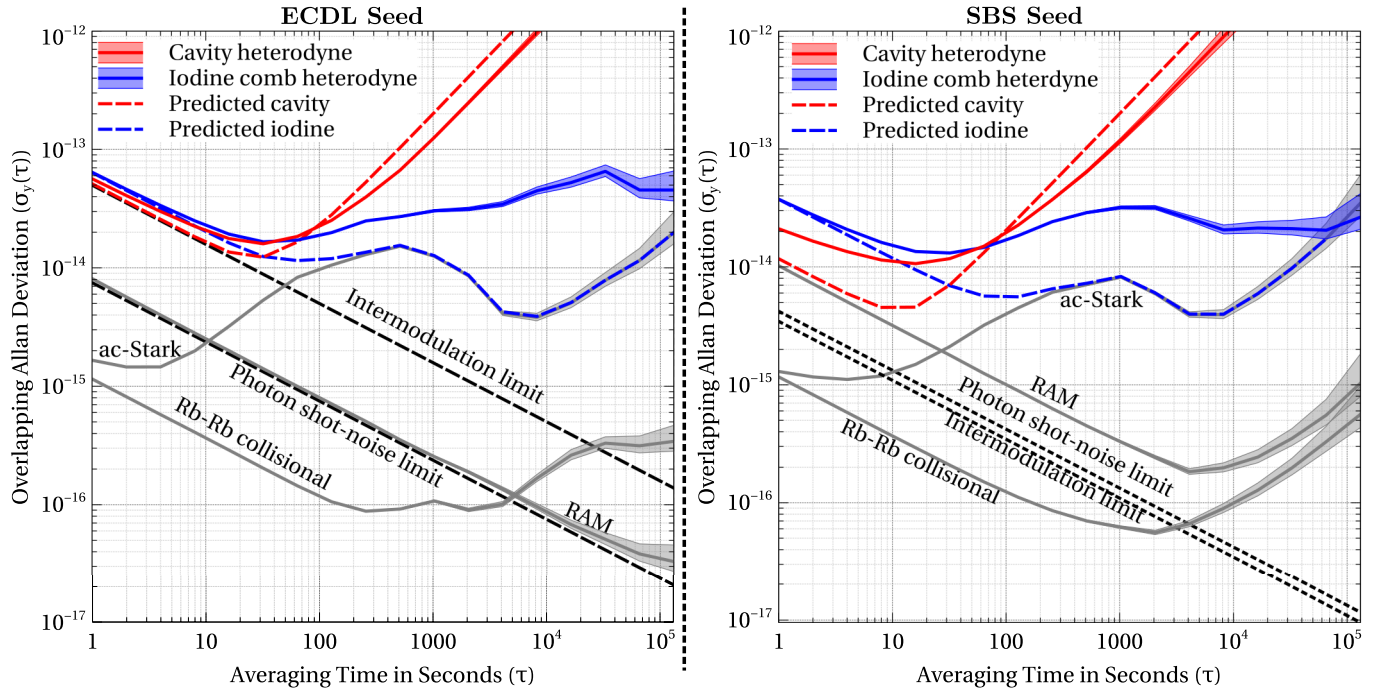


FIG. 4. Solid blue line shows the measured heterodyne between the iodine comb and the two-photon clock, while the dashed blue line shows the expected performance of this heterodyne, including expected reference instabilities and drifts. Solid red line shows the measured heterodyne between the cavity laser and the two-photon clock, while the dashed red line shows the expected performance of this heterodyne, including expected reference instabilities and drifts. Alongside the measured and expected clock performance are the measured environmentally driven instabilities: Rb-Rb collisional, RAM, and ac-Stark properly scaled to account for their impact on clock shift.

temperature led to variations in thermal load on the recirculating chiller resistor and materialized as temporary disturbances in stable baseplate temperature. This is the suspected cause for the bump at this timescale of both the expected and measured performance and the disagreement between measured and expected performance. Initially, small changes in optical alignment, driven by temperature fluctuations of the free-space optical breadboard, were suspected as the cause for this midterm mystery. Therefore, a silicon quadrant photodiode was placed at the rear-going pick-off location. Frequency stability data and environmental data were collected as the temperature set point of the free-space optical breadboard was varied. The total observed intensity of the light appears to vary under thermal fluctuations on the quadrant photodiode, a known problem with silicon detectors [63]; however, the location of the centroid moved under thermal fluctuations, see Fig. 5 for further details. Small heaters were also installed around each photodiode, the Glan polarizer, the fiber collimator, and the retroreflector. While shifts were measured while activating these heaters, no measurable frequency shifts were observed when the collimator heater was energized. The authors suspect that a combination of temperature gradients causing Rb-Rb pressure shifts, residual temperature-dependent photodiode detectivity

variations on the InGaAs photodiodes, and alignment ac-Stark shifts are the causes of both the midterm instability and the disagreement between expected and measured performance.

V. DISCUSSION

We prioritized improvement of short-term clock stability and have demonstrated that using an SBS laser in combination with increased optical intensities can reduce the short-term instability of this two-photon transition in Rb. With improvements in vapor cell assembly, laser design, and inclusion of the SBS, we were successful in increasing the short-term stability by more than an order of magnitude over our previous reports. However, this came at the cost of increased ac-Stark shift. Additionally, we discovered that RAM eventually becomes our largest source of instability in the short term. There exist methods of suppressing both RAM [38,60,61] and ac-Stark [62] in the literature, and this frequency standard, in its current form, would benefit from these mitigation techniques. Moreover, ovenization of the free-space optical components would yield improvements in midterm performance and is required for operation in the field. The results obtained here will be significant for the development of a deployable optical atomic clocks with high-frequency stability across all timescales. Deployable optical clocks are vital components that will become essential for future communication, navigation, and sensing technologies.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

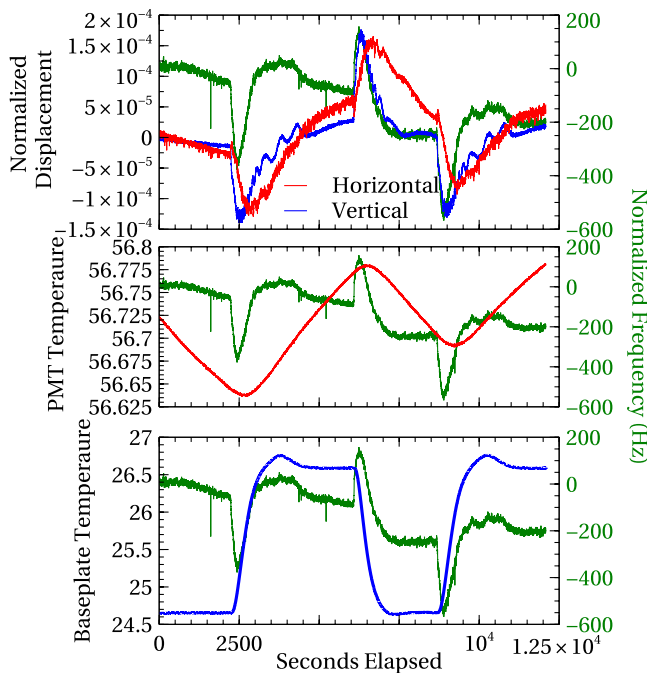


FIG. 5. The top graph shows the measured vertical (blue) and horizontal (red) alignment changes as the baseplate temperature is varied as well as the frequency shifts (green). The middle graph shows the PMT temperature change (red) and frequency change (green), and the bottom graph shows the baseplate temperature change (blue) along with frequency shifts (green).

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