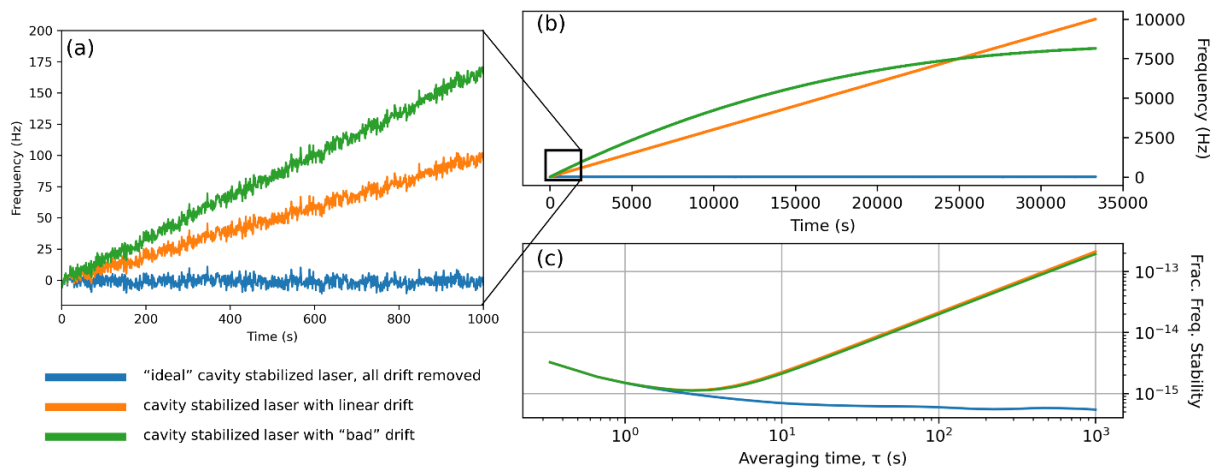


## Dual-reference approach for de-drifting an ultra-low-expansion cavity-stabilized laser

**Summary:** As atomic quantum computing and sensing platforms strive for increasing operational fidelities, there is a growing need for lasers that can maintain both fractional linewidth and frequency instability to better than a few parts in 100 trillion ( $\sim 5 \times 10^{-14}$ ). State-of-the-art ultra-low-expansion (ULE) cavity-stabilized lasers often satisfy the linewidth requirement, but their characteristic drift for averaging times beyond  $10^2$  seconds can result in significant fractional frequency instability. Atom-based quantum computing/sensing platforms traditionally have relied on their computing/sensing atoms as the sole absolute frequency reference for cavity de-drifting, but this approach can lead to frequent and consequential downtime. Here, we demonstrate a pathway toward a dual-reference approach where the cavity-stabilized laser is regularly referenced to Vescent's ultra-stable acetylene optical clock, which we call the Local Timing System (LTS), thereby reducing the need for traditional atomic corrections.



*Figure 1. Illustration of the relationship between cavity drift and fractional-frequency stability using simulated frequency data. (a & b) Type of drift is defined by how the central frequency of a cavity changes over time. (c) In a driftless cavity (blue), its fractional frequency stability will converge to the flicker-floor for long averaging times. In contrast, linear (orange) and non-linear (green) drift both lead to decreased stability.*

### Background and Case Introduction:

With the goal of exhibiting increased quantum control over atoms, high-performance atom-development for atomic clocks by adopting ultra-stable lasers with ultra-narrow (sub-Hz to 10 Hz) linewidths that reach Allan Deviations better than  $10^{-13}$  for averaging times  $\tau > 1$  s. [1-3].

Traditionally these lasers are created through frequency locking to high-finesse Fabry-Pérot cavities featuring high-reflectivity mirrors bonded to precision-machined spacers constructed from ultra-low expansion (ULE) glass. Because the length stability of the optical cavity is directly correlated to the frequency stability of the laser, multiple techniques are implemented to control cavity length fluctuations [4]. Careful mechanical isolation of the cavity reduces vibrations. Operating the cavity in a vacuum minimizes effective length drifts due to varying refractive index. Thermal fluctuations are diminished by holding the cavity at the zero-crossing temperature, where the thermal expansion coefficient of the ULE glass is zero. Careful applications of a combination of these approaches produce exceptionally narrow linewidths for averaging times up to  $\sim 10$  s.

For longer averaging times, further uncompensated drift leads to diminished fractional frequency stability. Ideally, the frequency of a cavity-stabilized laser remains centered around a single frequency resulting in a fractional frequency stability that will average down for long averaging times (Figure 1). If instead there is a source of drift, frequency stability worsens. Linear drift is largely predictable and thus straightforward to correct via feed-forward techniques. Correcting for non-linear or unpredictable frequency drift is more complex and requires referencing a robust absolute frequency source such as an environmentally insensitive atomic or molecular transition. Conveniently for atom-based platforms, the atoms at the core of the technology can act as the necessary reference. While atomic clocks reference their atoms without interrupting clock operation, quantum computing and sensing applications can be exposed to significant downtime when relying solely on internal atoms for cavity de-drifting.

As an example, we discuss an atom-based quantum computing platform recently encountered by Vescent. For the purposes of the application, the cavity-stabilized laser for probing the qubits needed to maintain a fractional frequency instability below  $1 \times 10^{-13}$  for all  $\tau$ . The cavity was sensitive to the thermal environment in the laboratory, leading to drift that caused instability to exceed the desired threshold for averaging times exceeding  $10^3$  s (Figure 2, pg. 3). This unpredictable drift was corrected by referencing the qubit atoms every 300 s in a process that interrupted quantum computation. While this procedure successfully stabilized the cavity, the resulting downtime was a significant time sink for the user.

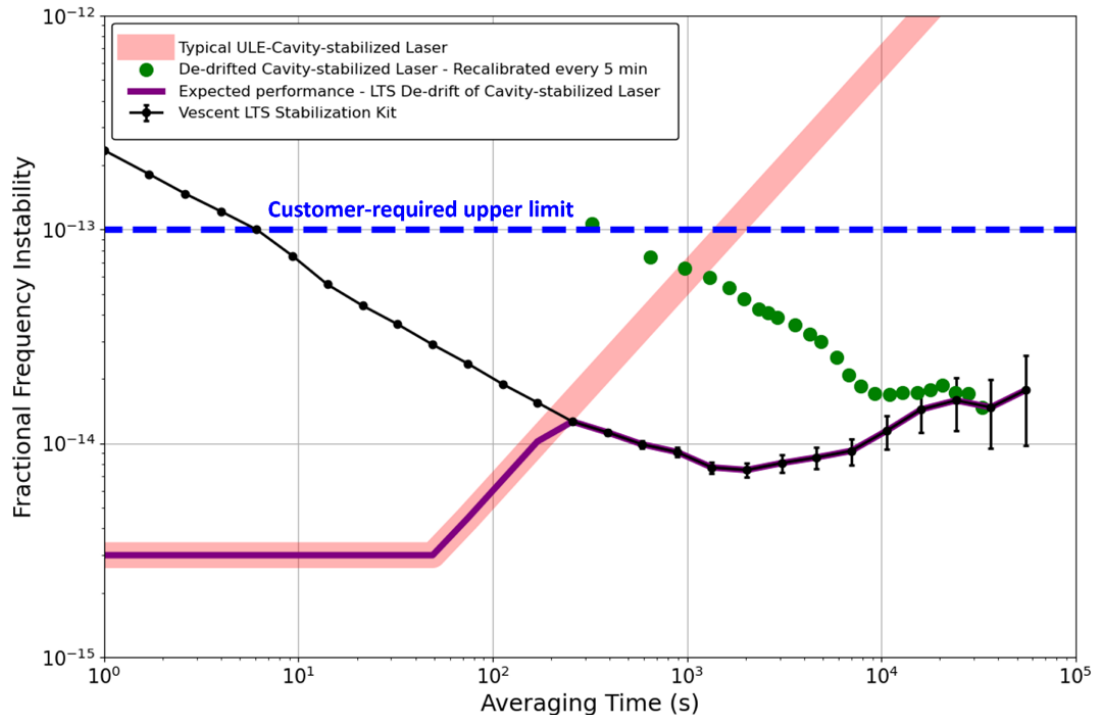


Figure 2. Over short time periods, well-designed cavity-stabilized lasers have exceptional frequency instability (red band). Controlling long-term drift, however, requires recalibration to a reference. In the studied case, recalibration to an atomic reference was needed every 300 seconds to keep frequency instability below the required limit (blue dash) leading to the performance seen in green (dots). For this platform, the de-drifting process is invasive to the quantum operation and leads to significant downtime. Instead, by performing de-drifting every minute using the Vescent LTS (black), satisfactory ULE performance can be extended significantly (purple band) without interfering with the quantum operation.

To significantly reduce the time burden on the atoms, Vescent worked with the quantum computing company to introduce an external ultra-stable frequency source that can be referenced instead of interrupting quantum computation. Below, we explore how the impressive stability of an acetylene-based frequency standard can be transferred to a relevant frequency via a fiber frequency comb and then harnessed by a cavity-stabilized laser. We will conclude by showing how this dual-reference method can be quickly implemented with commercial-off-the-shelf hardware using Vescent's environmentally robust Local Timing System (LTS).

## Principle of Stability Transfer

The Vescent LTS transfers the maser-like stability of a DFM Stabilaser 1542<sup>e</sup> frequency standard to the modes of a Vescent FFC-100 optical fiber frequency comb (FFC) such that the stability can then be accessed across a broad spectrum of optical frequencies. The Stabilaser is an acetylene-stabilized narrow linewidth laser that provides a robust frequency standard at 1542 nm. When the beat note,

$$(1) \quad f_{opt} = |f_n - f_{stable}| ,$$

between the Stabilaser frequency,  $f_{stable}$ , and mode  $f_n$  of the FFC is locked to an RF oscillator, the repetition rate  $f_{rep}$  of the fiber laser can be robustly fixed to,

$$(2) \quad f_{rep} = \frac{f_{stable} \pm f_{opt} \pm f_{CEO}}{n} ,$$

where  $f_{CEO}$  is the carrier-envelope offset frequency of the comb. Because  $n$  is large ( $n \approx 1.94 \times 10^6$ ) and the instability of the repetition rate is dominated by that of  $f_{stable}$ , the repetition rate is extremely well defined, and its stability approaches that of a state-of-the-art maser [5]. For any other comb mode,  $m$ , its absolute frequency instability is approximately defined by,

$$(3) \quad \partial f_m \approx \frac{m}{n} |\partial f_{stable}| ,$$

which is also the same as the approximate ratio between  $f_n$  and  $f_m$ . Thus, the fractional frequency stability of the stable reference is transferred to all modes of the comb.

## Example Layout

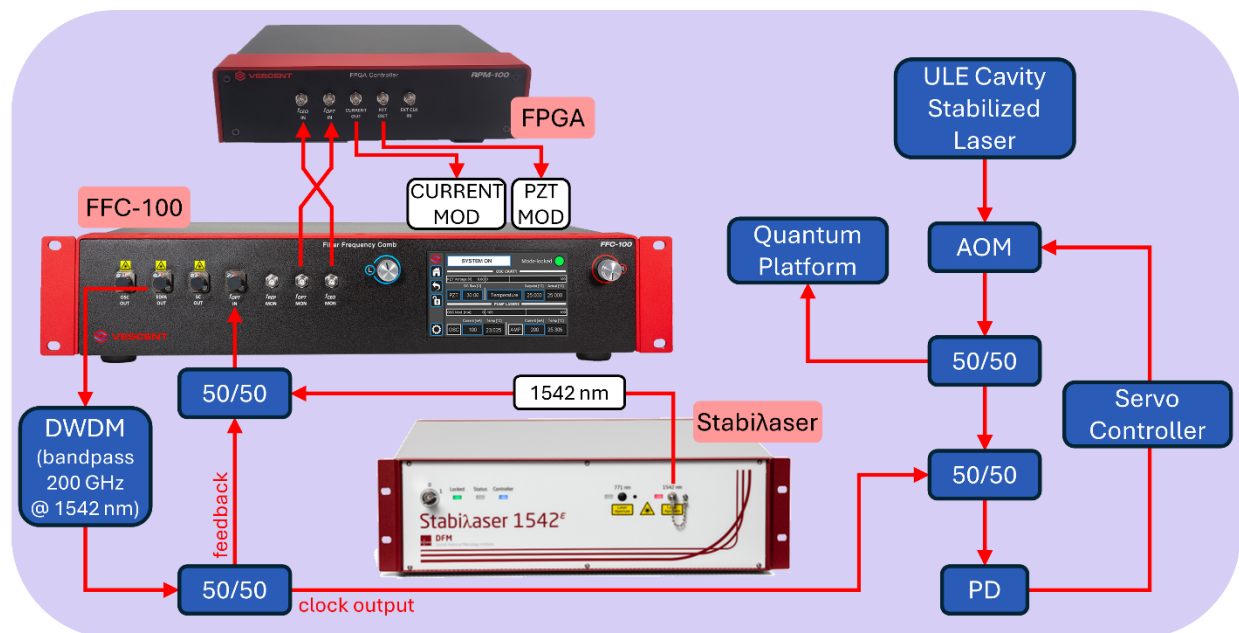


Figure 3. A high-quality optical clock reference is generated with a Vescent LTS, which includes a DFM Stablaser 1542<sup>®</sup> optical frequency reference, Vescent FFC-100 fiber frequency comb and Vescent SLICE-FPGA-II digital feedback controller. The output of the comb is filtered and split using a 50/50 fiber coupler. One port of the coupler is combined with the Stablaser to generate a beat note for offset phase locking. The second port is combined with light from the cavity-stabilized laser and the combined output is collected on a photodiode for heterodyne detection. This signal is fed to a servo controller (SLICE-FPGA-II) which can offset phase lock the laser frequency via control of an AOM.

The cavity-stabilized laser in the quantum computer exploits the frequency stability mentioned above by using the LTS as a frequency reference, as seen in Figure 3. The Vescent LTS includes all the hardware required to build the ultra-stable acetylene clock reference:

- (1) Vescent FFC-100 optical fiber frequency comb
- (2) Vescent SLICE-FPGA-II digital feedback controller
- (3) DFM Stablaser 1542<sup>®</sup> acetylene-stabilized narrow linewidth laser

Setting up the LTS, including installation and warm-up, takes less than 30 minutes. The LTS components are plugged directly into line power and require no vibrational or environmental isolation.

The clock operation is summarized as follows: the output of the FFC is sent through a Dense Wavelength Division Multiplexer (DWDM) which acts as a bandpass filter and isolates the comb

modes in a 200 GHz band around 1542 nm. The filtered beam is split into feedback and clock output signals by a fiber splitter. The feedback is combined with the output of the StabiLaser, resulting in a heterodyne beat note frequency ( $f_{opt}$ ) defined as the difference between the frequency of optical mode  $n$  of the FFC ( $f_n$ ) and the frequency of the StabiLaser ( $f_{stable}$ ). The optical beat note ( $f_{opt}$ ) is detected in the FFC-100 and a high signal-to-noise RF signal is generated.

Both the  $f_{opt}$  beat note and the carrier-envelope offset signal ( $f_{CEO}$ ), originating in the FFC, are monitored by the FPGA. The FPGA performs a proportional-integral-derivative (PID) lock of  $f_{opt}$  to an internal RF oscillator and outputs the signal to the “PZT MOD” input on the back of the FFC. Inside the FFC, a high-speed actuator controls the nominally 100 MHz comb repetition rate ( $f_{rep}$ ), which is now set by the relation in equation 2. Similarly, the FPGA performs a separate PID lock of  $f_{CEO}$  to a second internal RF oscillator and outputs the signal to the “CURRENT MOD” input on the back of the FFC which exercises control over the oscillator pump diode power. Through these processes,  $f_{rep}$  and  $f_{CEO}$  are fully stabilized and the frequency stability of the StabiLaser is transferred to all modes of the comb.

Returning to the DWDM, half of the stabilized, filtered clock output signal is sent to be combined with the cavity-stabilized laser light. In this example the frequency of the StabiLaser and the cavity-stabilized laser are separated by only 30 GHz. Note, since these signals both fall within the same narrow frequency band defined by the DWDM, it is convenient to use one filter in this setup. That said, by an appropriate choice of splitters and filters, it is possible to extend this approach for any laser with an emission frequency that overlaps the FFC spectrum. The combined beams are captured on a photodiode and the signal is sent to a servo controller (e.g., a SLICE-FPGA-II), which controls the frequency of the experiment light via an acousto-optic modulator (AOM). In this way, the quantum computing probe beam can be locked to the LTS stable frequency reference.

The set-up for the dual reference method is now complete. The cavity-stabilized laser is referenced to the LTS approximately once a minute to suppress drift. This coerces the instability of the probe laser to approach the instability profile of the StabiLaser for averaging times above  $10^2$  seconds. The StabiLaser is insensitive to the temperature fluctuations commonly encountered in laboratory environments, making it an ideal reference in this scenario. Long-term drift will still occur over timescales  $> 10^4$  s, making it necessary to again rely on the atoms for reference (Figure 2). Importantly though, the referencing burden on the atoms is decreased significantly. In the above example, the disruptive action of atomic referencing within the quantum computer is required about 30x less often with the dual-reference method – every few

hours rather than every few minutes – resulting in a corresponding increase in computational uptime.

**Conclusion:** We discussed a dual-reference method for de-drifting a ULE cavity-stabilized laser. In the case studied adding the Vescent LTS as a second stable, environmentally robust frequency source enables the quantum computing platform to rely less on its internal atoms for referencing, which ultimately leads to significantly more apparatus uptime.

**References:**

- [1] X. Jiang, J. Scott, M. Friesen, and M. Saffman, "Sensitivity of quantum gate fidelity to laser phase and intensity noise," *Phys. Rev. A* **107**, 042611, 2023.
- [2] M. L. Day, P. J. Low, B. White, R. Islam, C. Senko, "Limits on atomic qubit control from laser noise," *npj Quantum Information*, 8:72, 2022.
- [3] OC18 Consortium, "Guidelines for developing optical clocks with  $10^{-18}$  fractional frequency uncertainty", arXiv:1906.11495, 2019.
- [4] J. A. Boyd, T. Lahaye, "A basic introduction to ultrastable optical cavities for laser stabilization," *Am. J. Phys.* 92, 50-58, 2024.
- [5] Vescent, "An acetylene optical clock with maser-like performance assembled from commercially available products," Application Notes, 16 January 2024.