Integrating Optical-Clock Technology into an Operational Timescale

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***Summary*— We present a scheme for integrating optical clock technology into an operational timescale. Using a telecom laser stabilized to a high-finesse cavity and an optical frequency comb, we generate low-phase noise microwaves that can be steered using a rubidium (Rb) fountain clock to improve long-term stability. The optical system has promising robustness and improves the performance of the Rb fountain. The photonic microwave can be integrated directly into the timescale for the best short-term performance, or used to steer a H maser for maximum reliability.**

Keywords—Rubidium fountain clock; optical frequency comb; continuous timescale; photonically generated microwaves

I. Introduction

Advancements in optical clocks have had a dramatic impact on frequency metrology, yet it is a challenge to harness these complex optical systems for operational timing where continuous operation is required. The several demonstrations of incorporating optical clocks into timescales have typically used the optical system to steer a hydrogen maser, or maser ensemble, intermittently [1-3]. This extends the technique of steering a maser with a microwave clock, such as an atomic fountain, and the short-term performance is always limited by the maser and synthesizer used for steering [4-5].

Here we discuss more fully integrating optical technology into operational timescales by producing a stable and reliable optical signal that is converted to RF and fed directly to a measurement system, without relying on a maser and preserving the stability of the optical signal at short averaging times. While an optical lattice can be used to provide long-term stability, even the best systems experience enough downtime to make this currently untenable for an operational timescale. Instead, we discipline the optical oscillator to a continuously running atomic fountain, providing a long-term reference with proven reliability [6].

II. Maser-based Timescale

Timescales are often realized using a hydrogen maser and a precision synthesizer as shown in Fig. 1(a). The synthesizer, in our case an auxiliary output generator (AOG), recreates the maser frequency with fine frequency or phase adjustments as directed by the clock(s) comprising the timescale. The reliability of hydrogen masers and high-resolution synthesizers make these essential tools for operational timing, when clock and timescale outputs must be available without interruption.

Comparisons between timescale clocks and the reference maser are used to compute frequency adjustments communicated to the AOG. There may be many devices comprising the timescale clocks, or just one device, such as an atomic fountain or optical lattice clock. The frequency stability of a maser-based timescale cannot surpass that of the reference maser at times shorter than the steering time constant. In the long-term, the timescale can average down to the white-frequency-noise level of the better clock(s). The final timescale performance will depend on a variety of factors, including the stability and the uptime of the clock applying the steers.

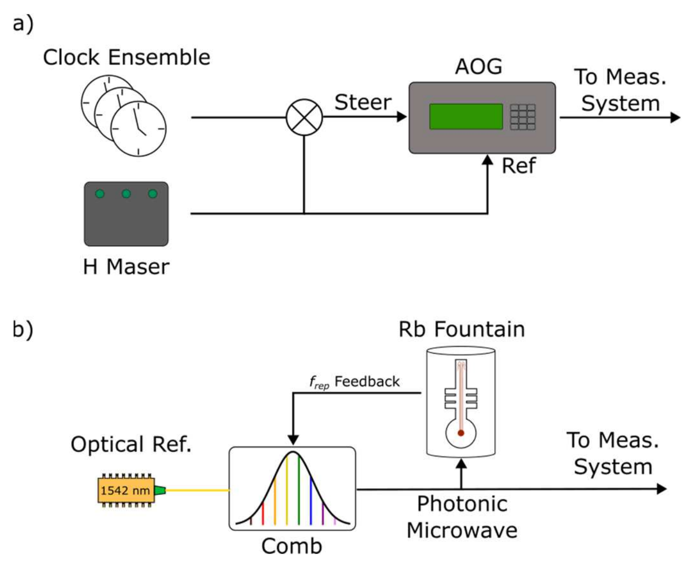

Figure 1 (a) Illustration of a steered maser or “maser-based timescale”. One or more clocks send frequency adjustments to a precision synthesizer, which reproduces the reference maser frequency with the corresponding adjustment. (b) Illustration of fountain operated with low-noise microwave chain and removing the drift of the optical oscillator.

III. Optical Oscillator-based Timescale

If an optically derived RF signal can be generated reliably, the maser and AOG can be circumvented and the high stability of the optical oscillator can be available for short averaging times. While a continuously available all-optical signal may not be realistic in the immediate future due to the complexity of cold-atom optical clock systems, the optical oscillator serving as the local oscillator (LO) for optical clocks can be quite robust. Optical lattice clocks may use up to 7 independent CW lasers, while an optical LO is comprised of a single CW laser and a frequency comb.

The optical oscillator used here is a telecom-grade 1542 nm laser locked to a high-finesse optical cavity with crystalline mirror coatings. The laser is used to stabilize an optical frequency comb, which converts the optical signal into radio-frequency signals at the comb repetition rate and harmonics with frequency stability comparable to the optical reference, and these in turn are used to produce 10 GHz, 200 MHz and 5 MHz signals required for clock measurement systems. Made with all telecom wavelength components, this optical oscillator has been robust, continually outputting an RF signal for over seven months.

The fractional frequency stability of the optical oscillator is below 10^{-15} at 1 s. The generation of lower frequency RF signals can degrade the stability somewhat, though an RF output with 1s instability below 10^{-14} is realistic. Drift in the ULE optical cavity of $\sim 10^{-16}\ s^{-1}$ negatively impacts long-term stability, but long-term performance can be improved by disciplining the optical oscillator to an operational rubidium fountain [6]. For further redundancy a hydrogen maser can be steered to follow the photonic microwaves. This produces an output limited by the maser performance in the short term, as discussed in the previous section, but optimizes robustness.

The low phase noise of the photonic microwave improves the performance of the fountain. The frequency instability of a fountain clock has contributions from the atomic quantum projection noise (QPN), technical noise, and the microwave drive. By using the photonically derived RF as the basis for the fountain's microwave chain, the overall stability is improved by as much as a factor of three over the performance when using a quartz crystal. If the optical phase noise is low enough, the limit of the fountain performance is the QPN, which has been measured in our system to be about 5×10^{-14} at 1 s. The fountain measures and compensates for the drift of the optical cavity by adjusting the repetition rate of the frequency comb.

The 5 MHz signal from the optical oscillator can be measured directly with the same clock measurement system used to measure more than 100 atomic clocks at USNO regularly. These measurements are subsequently used to derive clock weights and produce UTC(USNO). Noise in the currently used clock measurement system interferes with measurement of high-stability signals at short averaging times. Over the long term, we can verify that the steered optical oscillator reflects fountain performance expected. In Fig. 2 we show the phase difference of the rubidium fountain and UTC(USNO), measured as part of an operational clock ensemble. The first part of the phase record reflects the traditional method of steering a maser with the fountain; during the second part, the optical oscillator is used, and the same maser is steered to the optical LO. No change in slope is observed between the two sections of the phase record indicating that the optical LO accurately follows the fountain frequency.

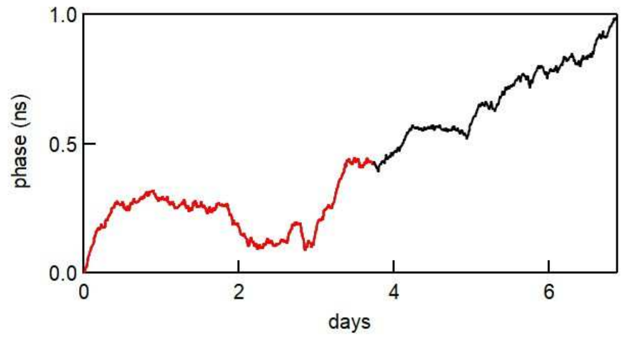

Figure 2 Phase difference between rubidium fountain and UTC(USNO). The first portion of the data (red) is when fountain operated conventionally; second portion (black) is when the fountain is steering an OLO.

IV. FUTURE

The narrow laser and frequency comb are part of a larger, more complex laser system that will be used to operate a strontium optical lattice clock. Once that is online, the rubidium fountain can be used for holdover during periods when the strontium lattice is unavailable. The result will be an optical - and derived RF - signal with short-term stability provided by the narrow laser and long-term stability by a strontium lattice (expected parts in 10^{15} white-frequency noise level) when available and a rubidium fountain (on order of 5×10^{-14}) for all other times.

We have proposed and implemented a scheme for integrating an optical oscillator into a continuous timescale by steering the low-noise output of an optical frequency comb to a Rb fountain. The reliability and performance of optical clocks continues to improve and may someday reach the point where masers and AOGs can truly be replaced. New architectures and measurement system designs will be needed to take advantage of the improved performance and provide the necessary redundancy required for continuous timescale generation.

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