COMPACT MICROWAVE MERCURY ION CLOCK FOR SPACE APPLICATIONS

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Abstract

We review progress in developing a small Hg ion clock for space operation based on a breadboard ion-clock physics package where Hg ions are shuttled between a quadrupole and a 16-pole rf trap. With this architecture, we have demonstrated a short-term stability ~ 1-2×10^{-13} at 1 second, averaging to 10^{-15} at 1 day. This development shows that H-maser quality stabilities can be produced in a small clock package, comparable in size to an ultra-stable quartz oscillator required for holding 1-2×10^{-13} at 1 second. We have completed an ion clock physics package designed to withstand vibration of launch and are currently building a ~ 1 kg engineering model for test. We also discuss frequency steering software algorithms that simultaneously measure ion signal size and lamp light output, useful for long-term operation and self-optimization of microwave power and return engineering data.

I. INTRODUCTION

Long-term timekeeping onboard Earth orbiters such as GPS, Galileo, and other programs can be provided by a small, reliable ultra-stable atomic clock. In this paper, we describe a small ion clock currently being developed for space operation with a frequency stability 10-100 times better than that of the best GPS Rb clocks. We have completed the physics package design (mass ~ 1 kg) and are now fabricating the parts of this small space-qualified designed frequency standard. This package is based on a breadboard device previously described **[1]** and maintains the trapping structures and improves optical collection used for atomic state selection, but aggressively integrates the vacuum tube, optical windows, magnetic shields, and mounting structure to reach this very low mass. The vacuum tube materials are chosen so that the tube can be de-gassed to ~ 450°C, then filled with a trace amount of ^{199}Hg and sealed. Gas flow-through methods as used in Cs-beam and H-maser clocks are not employed; consequently, no consumables are present to limit operational lifetime.

We will describe in this paper a novel frequency tracking method that allows monitoring and optimization of various engineering data, and will also permit fast tracking of USO or other local oscillator frequency hops.

II. PHYSICS PACKAGE STATUS

The physics package is shown in Figure 1. The mechanical package shown is designed to withstand generic random vibration levels of over 9.2 g_{rms}. A modal analysis was made of the structure using more than 3000 nodal mesh points to determine resonance frequencies of various mechanical subassemblies. All frequencies are 200 Hz and higher, adequate for many launch requirements. Various electronics circuit boards can be designed to conform to the spaces available within this structure. The functional layout is described in Ref. **[1]**.

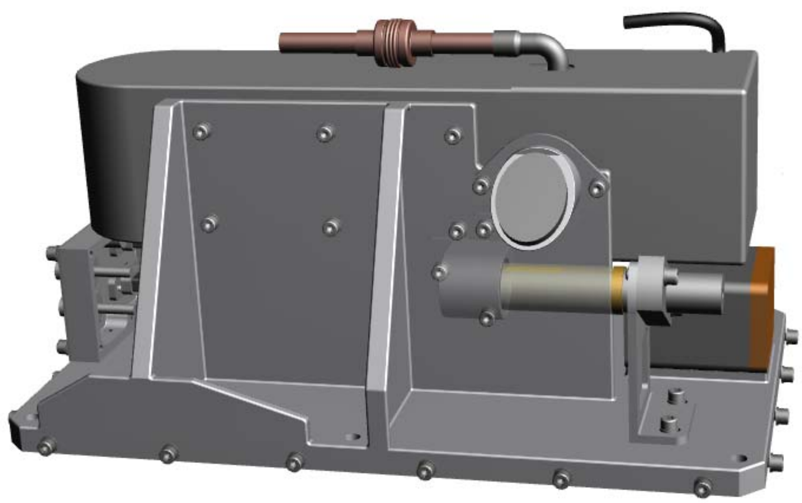

Figure 1. The ~ 3 liter physics package with baseplate, photomultiplier tube, and vacuum tube mounting through the two-layer magnetic shield. The outer magnetic shield is not shown.

III. LAMP LIFETIME STRATEGIES

The ion clock relies on optical pumping to prepare and to detect the $^{199}Hg^{+}$ microwave 40.5 GHz transition. The light source is a fused silica bulb ~ 12 mm diameter by ~ 30 mm in length filled to ~ 1 torr argon buffer gas with a quantity of metallic ^{202}Hg. The lamp is excited at ~ 200 MHz inside a resonant LC tank circuit, with the bulb placed inside a two-turn coil to inductively excite a discharge inside. Typically, 10 W are dissipated within the exciter circuit and bulb for bright-mode operation. Under these and similar operating conditions, lamps have functioned well for 5 years or more.

For in-vacuum space operation, we have housed the lamp bulb in a package similar to the GPS rubidium clock **[2]**. That is, the bulb and exciter coil are placed inside an ovenized container, with the bulb potted in an indium thermal heat sink base to maintain and control the cold point temperature and, consequently, vapor pressure of Hg inside the sealed bulb.

Mercury lamps are used in many applications to create UV light for water purification and sterilization. UV transmitting materials become opaque over time when exposed to high fluxes of

UV light and possible chemical interactions with Hg vapor inside, as hundreds of watts of power are used to generate either 254 nm or 185 nm light. This degradation is similar to the slow darkening seen in our Hg clock application, though the rate of darkening is accelerated because of the higher power and temperature used in UV light purification/sterilization applications.

Alternate materials have been investigated which may be more resistant to chemical reactions with Hg and also more UV-resistant. The most successful of these is sapphire, as described by Hereaus **[3]**, where a sapphire coating the inside of the fused silica bulb acts as a barrier to chemical reactions where HgO is formed near the surface of the SiO_2 bulb. The pictures **[3]** show a dramatic decrease in darkening of the glass when sapphire is applied. Other materials and a description of the process is given in Ref. **[4]**.

Sapphire bulb material has been proposed for use in GPS rubidium. Some test rubidium bulbs were built **[5]** and showed behavior similar to conventional glass bulbs.

IV. NOVEL LINE ACQUISITION METHODS

The ion clock resonance signal shown in Figure 2 is derived from the classic Rabi single microwave square-wave pulse **[6]**. The resonance linewidth is determined by the duration, T, of the pulse. The resulting frequency linewidth is 0.799/T ~ 0.27 Hz for the measurement shown in Figure 2, corresponding to a 3-second microwave pulse.

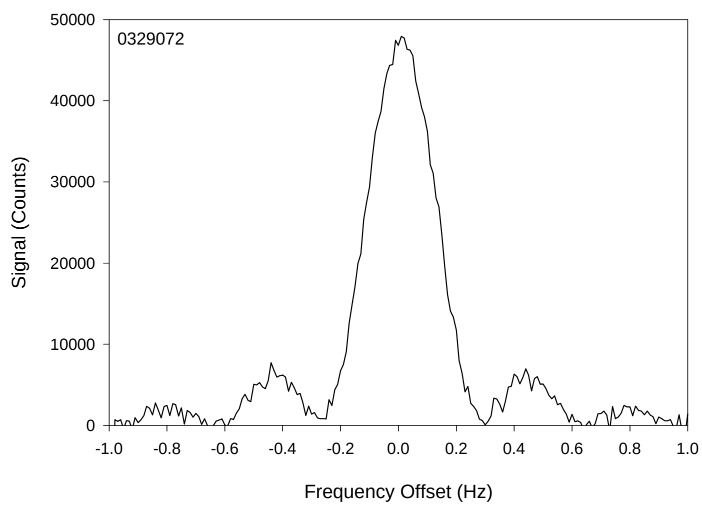

Figure 2. The measured ^{199}Hg ion clock resonance line near 40.507 GHz. Fluorescence vs. frequency is plotted. Fluorescence is recorded digitally as the total number of photon pulses accumulated in an approximately 2-second time interval.

To measure the $^{199}Hg^{+}$ clock reference frequency, the output of a tracking synthesizer is typically stepped to either side of the resonance line-center, to the points of steepest frequency slope. The sequence of measurements yields a sequence of numbers, C(1), C(2), C(3),…C(n), each the number of photon pulses accumulated in some time interval, usually 2 seconds or less. Such successive fluorescence measurements are made on opposite sides of line-center. The simplest proportional loop adjusts the center frequency of modulation according to $\Delta f \propto R_{loop} Lw \frac{C(1)+C(3)-2C(2)}{2\pi\, SignalSize}$ in order to "track" the line-center. In this expression, *Lw* is the linewidth (.799/T for the Rabi interrogation) and *SignalSize* is the height of the resonance signal above background light level, as shown in Figure 2. The sequence of frequency corrections, Δf, are summed so that the tracking synthesizer approaches the line-center approximately exponentially. The "second difference" *C(1)+C(3)-2C(2)* is used so that linear drifts in the UV light source output will not cause a frequency offset.

Signal size depends on several variables, including the microwave power, so that occasionally the sequence of frequency measurements is interrupted to measure the signal size via fluorescence measurements on line-center and several linewidths away from line-center, typically 1 Hz or more.

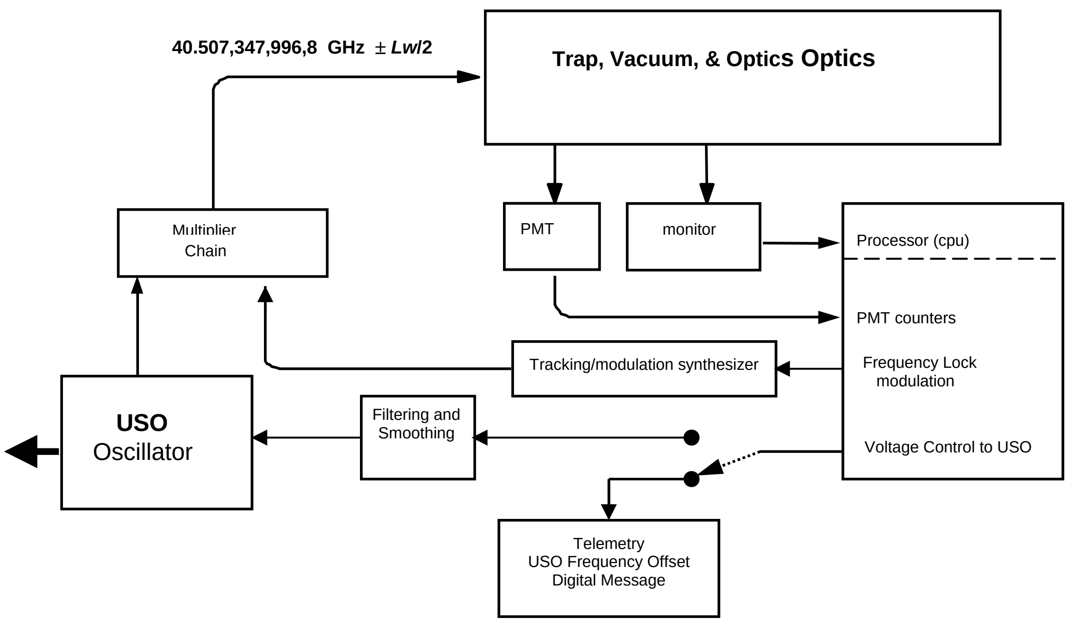

Figure 3. Block Diagram of the frequency lock loop.

Another method of determining the line-center is based upon the analytical expression for the Rabi line-shape **[4]**,

$$P = \frac{(2b)^2}{(\omega-\omega_0)^2+(2b)^2}\sin^2\left(\frac{T}{2}\sqrt{(\omega-\omega_0)^2+(2b)^2}\right) = \frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+y^2}\right)}{1+y^2} \equiv Rabi(y), \text{ where}$$

$$y^2 = \frac{(\omega-\omega_0)^2}{(2b)^2} = \left(2T(\nu-\nu_0)\right)^2$$ and we have assumed that the power is optimized, $bT = \frac{\pi}{2}$.

The steepest point for use in frequency discrimination occur at $y \cong \pm\, 0.761$, while the half-max points occur at $y \cong \pm\, 0.799$.

In practice, the Rabi resonance line-shape is a very good model for the measured signal, as shown in Figure 2. The full measurement yields a background light level, *Bck* , a signal-size, *Amp*, and a line-center frequency, ε. The total light collected vs. frequency is thus described by three parameters as $Light = Bck + Amp * Rabi(y - \varepsilon)$. A method for measuring frequency stability of the resonance line would be to make three frequency measures, as shown in Figure 4, and invert the equation $Light = Bck + Amp * Rabi(y - \varepsilon)$ to extract values for *Bck*, *Amp*, and ε.

This method allows frequency tracking of the line-center and collection of engineering data of both lamp light output and signal size. The signal size measurement can be used to continuously optimize microwave power levels, a useful measurement for long-term autonomous clock operation. This line acquisition method is complete in three measurements, unlike the proportional method described earlier, which only approaches line-center exponentially.

In practice, three measurements, C(1), C(2), and C(3), are made at different frequencies y_1, y_2, and y_3. The following three equations are then inverted:

$$C(1) = Bck + Amp * Rabi(y_1 - \varepsilon)$$
$$C(2) = Bck + Amp * Rabi(y_2 - \varepsilon)$$
$$C(3) = Bck + Amp * Rabi(y_3 - \varepsilon)$$

Three values for y are shown in Figure 4, $y \cong \pm 0.761$ and $y = 0$.

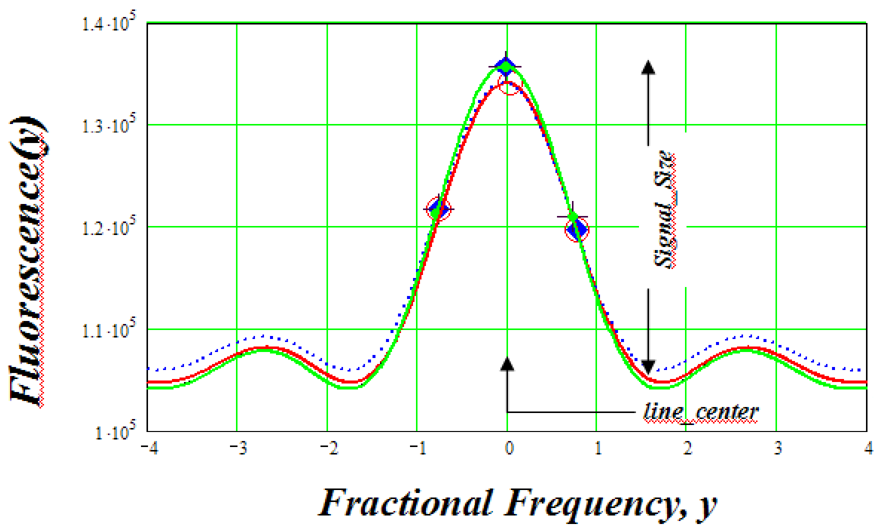

Figure 4. The theoretical Rabi line-shape with a constant background light level Bck = 105,000 counts and Signal Size = Amp = 30,000. A signal-to-noise level of ~ 30 has been simulated, and three successive solutions are shown.

To monitor the line-center frequency, the three most recent measurements are used as described above to determine line-center frequency, background light level, and signal size. Every measurement is followed by an inversion of the three equations and yields a new set of parameter estimates. Figure 5 shows simulated frequency tracking where the center frequency is changed from $\boldsymbol{y} = 0$ to $\boldsymbol{y} = -0.75$ at step 10 of the 100-step sequence. This simulation is based on an average signal-to-noise ratio of ~ 32. The response time is very fast compared to the proportional methods. The step size of this instantaneous line-center change can be too large for the tracking to follow, in part because, far from line-center, there may not be a unique inverse solution to the three equations at the heart of the method. This non-uniqueness can also cause problems as the signal-to-noise ratio diminishes.

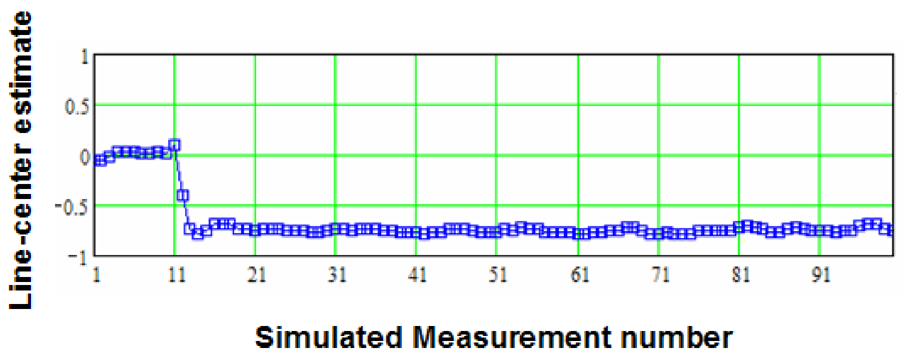

Figure 5. The response of the tracking algorithm is shown for an instantaneous change in line-center (at step 10) by $\Delta y = 0.75$.

Because this method separates the influences of background light, signal size, and line-center, a linear drift in the light level from the lamp does not seem to force a frequency pulling of the estimated line-center. Figure 6 shows a simulated large light-level drift imposed over the simulated frequency tracking noise data, with no evidence of frequency pulling.

We have tested this algorithm in laboratory measurements where the $^{199}Hg^{+}$ ion frequency was tracked using an H-maser local oscillator. The magnetic shields for the ion clock were removed so that ambient magnetic fields would change the clock frequency, to test the algorithm's ability to follow changes. The Allan deviation of the resulting sequence of line-center frequency estimates is shown in Figure 7.

V. ACKNOWLEDGMENTS

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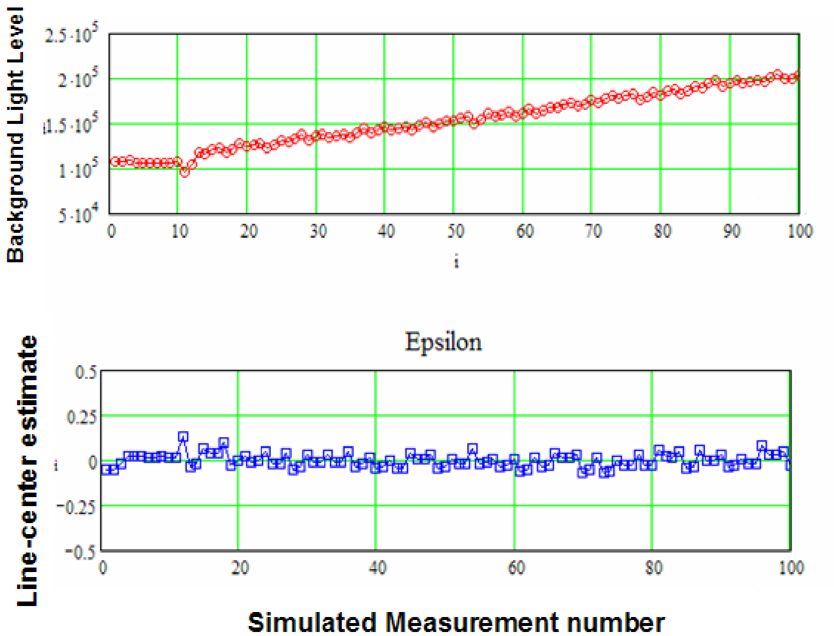

Figure 6. The non-linear curve-fit tracking algorithm does not show a frequency shift when the light-source drifts in its ouput level. In the above simulated line tracking, a large linear drift was imposed on the light level starting at measurement 10.

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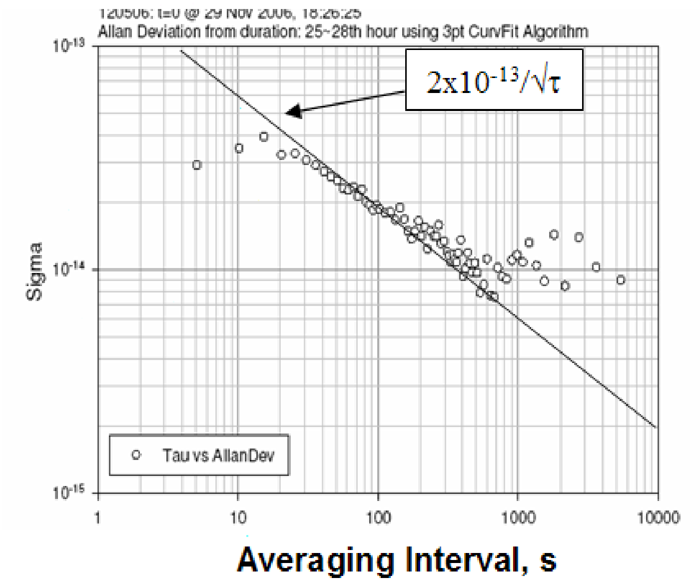

Figure 7. In-lab frequency tracking of the $^{199}Hg^{+}$ clock transition using the non-linear curve-fit tracking algorithm, as outlined in this paper. During this measurement, the ion clock magnetic shields were removed, resulting in frequency instabilities beyond a 1000-second averaging interval.