Compact Microwave Mercury Ion Clock for Deep-Space Applications

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Abstract— **We have recently completed a breadboard ion-clock physics package based on Hg ions shuttled between a quadrupole and a 16-pole rf trap. With this architecture we have demonstrated short-term stability ~1-2x10^{-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 1-2x10^{-13} at 1 second. This performance was obtained in a sealed vacuum configuration where only a getter pump was used to maintain vacuum. The vacuum tube containing the traps has now been under sealed vacuum conditions for nearly two years with no measurable degradation of ion trapping lifetimes or clock short-term performance. We have fabricated the vacuum tube, ion trap and UV windows from materials that will allow a ~ 400°C tube bake-out to prepare for tube seal-off. This approach to the vacuum follows the methods used in flight vacuum tube electronics, such as flight TWTA's where tube operation lifetime and shelf life of up to 15 years is achieved. We use neon as a buffer gas with 2-3 times less pressure induced frequency pulling than helium and, being heavier, negligible diffusion losses will occur over the operation lifetime.**

I. INTRODUCTION

A small space-qualified atomic frequency standard with stability as good as 10^{-15} over several hours averaging interval would enable one-way deep space navigations, where Doppler data is accumulated in a down-link only fashion. Currently, deep space navigation is implemented by measuring the Doppler frequency shift of a 2-way link from a ground station to a spacecraft (s/c) and the coherent return link. Typically, these links are maintained for 7-8 hours per s/c track, requiring full use of a 34-meter antenna in the Deep Space Network (DSN) for the time the s/c is sufficiently above the horizon.

When more than one s/c orbit around the same planet, they can be tracked simultaneously with one antenna. Multiple s/c tracking by a single antenna can reduce antenna usage and DSN costs.

II. SEALED VACUUM TESTS

A major step toward miniaturizing the ion-clock technology has been the elimination of all mechanical and electrical vacuum pumps from the physics package. Following the methods of space Traveling Wave Tube Amplifier (TWTA) fabrication we have chosen vacuum materials that can withstand a bake-out to ~ 400°C. In particular, glass-to-metal seals for electrical feedthrus, microwave windows, and UV optical windows often limit bake-out temperatures to 200°C. Non-magnetic tube materials are also required since field gradients can limit high atomic-Q operation. We find that titanium-to-alumina and titanium-to-sapphire joints are a practical solution since these joints can be baked to 400°C and VUV grade sapphire can transmit 194 nm. We do not use polarized UV light so the optical anisotropy of the sapphire is not an issue.

In this way, the vacuum system was baked out on the pump-stand then backfilled with Neon to about 10^{-6} Torr. The system was then sealed with a small ultra-high vacuum valve The best indication of vacuum quality inside the tube is the length of time that ions are maintained within the trap following ion loading. Figure 1 shows ion-trapping time data measured nearly a year following the tube seal-off from the pump stand. An ion tube pumped by a turbo followed by low temperature bakeout shows typical trapping times of ~ 1 hour. By contrast, the measurements of Figure 1 demonstrate that ions are held several hundred to one thousand times longer in the tube baked and sealed as described above.

The tube was charged with ^{199}Hg vapor from a small appendage HgO oven. The large turbo-pumped ground units operate with continuous heat applied to the oven, initially at temperature ~ 200°C and increasing to near 300°C over years of operation indicating that Hg becomes more difficult to dissociate over time [1]. By contrast, if the HgO oven remained at ~ 200°C following tube seal-off, Hg vapor would build-up so high that the clock signal would vanish due to charge transfer between the state selected trapped ions and the parent neutral vapor. At a residual Hg pressure of 10^{-8} Torr, the time for charge transfer with a state selected trapped ion is ~ 1 second [2].

To prevent Hg buildup the HgO oven is left at ambient temperature and only heated above room temperature when signal size falls. Following this Hg charging operation, the HgO oven can remain at room temperature for months or longer. The interplay between Hg vapor and ion signal size is shown in the measurement time sequence of Figure 2. Plotted there is ion clock signal size and mercury vapor pressure. Both these quantities are measured via fluorescence collected in the PMT optical collection arm. The neutral vapor coincidently fluoresces on the 185 nm transition $6^1S_0 \leftrightarrow 6^1P_1$, well within the bandwidth of our fluorescence detection system, designed for fluorescence of the Hg^+ ion transition at 194 nm. Both lines are generated within the Hg UV lamp.

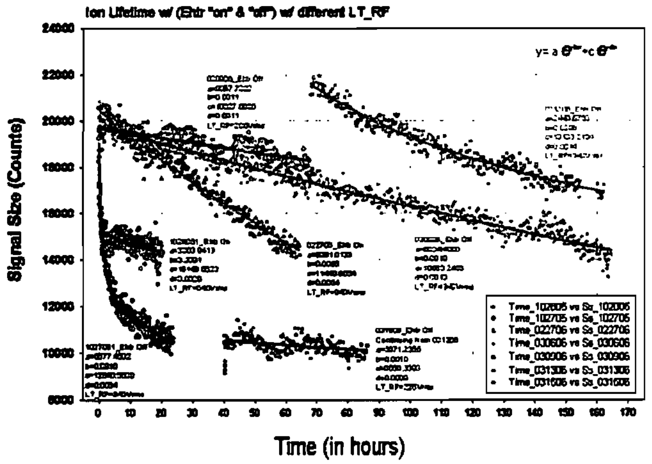

Figure 1. Ion trap times are determined by decay of the 40.5 GHz clock signal over time. The above span covers 170 hrs (~ 7 d). The time to 1/e of the initial signal size varied from 400-500 hours to 1000 hours.

At ~ 0.25 hour, the HgO oven heater is pulsed to 270°C for about 1 minute generating Hg neutral vapor, scattering 185 nm UV light as shown in the solid line plot. This excess neutral vapor forces the ion clock-signal size to diminish as charge transfer degrades optical state selection of the trapped ions. As the vapor is deposited on the vacuum tube walls, on the getter elements, and back onto the cooled HgO, the ion clock signal returns within about ½ hour. In a similar way, Hg vapor can be generated by heat applied to the getter elements. This shows that there is enough residual mercury in the tube for clock operation without degradation of signal size through charge transfer. Also we can conclude that there are adequate reserves of Hg within the tube to generate more vapor if needed to load ions into the trap.

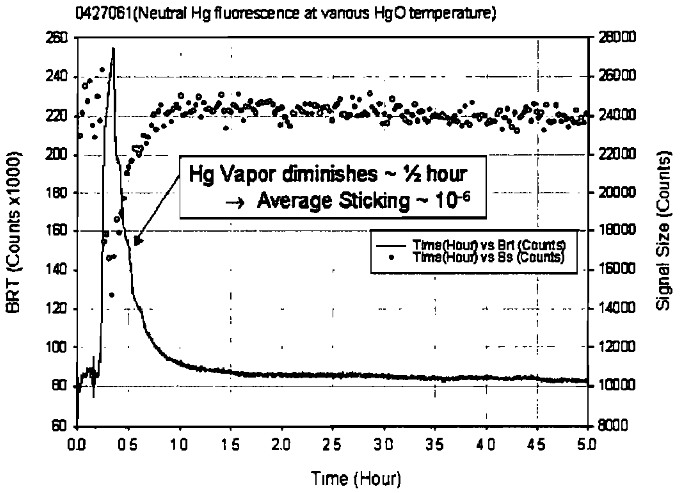

Figure 2. Simultaneous measurements of 194 nm fluorescence from trapped $^{199}Hg^+$ ions (red) and 185 nm neutral ^{199}Hg vapor (black). HgO oven is brought to ~ 270°C for ~ 1 minute at 0.25 hour. During the ~1/2 hour decay of the neutral vapor the Hg atoms transit the liter sized tube ~ 10^6 times demonstrating that the *average* sticking coefficient for Hg on the internal surfaces is ~ 10^{-6}.

III. MINIATURIZED ION CLOCK PHYSICS PACKAGE

We are finalizing the physics package design consistent with a 3-liter total package volume. Much size reduction of the physics tube comes about by fabricating a custom integrated tube. The ion traps for loading/optical state selection and for microwave resonance interrogation are the same size as in the breadboard unit. Similarly, the clear area of the UV windows is equal to that of the breadboard flange mounted windows. A cutaway design sketch of ion traps held inside the vacuum tube is shown in Figure 3 which will be residing inside a three layered magnetic shields of 3-liter total package shown in Figure 4.

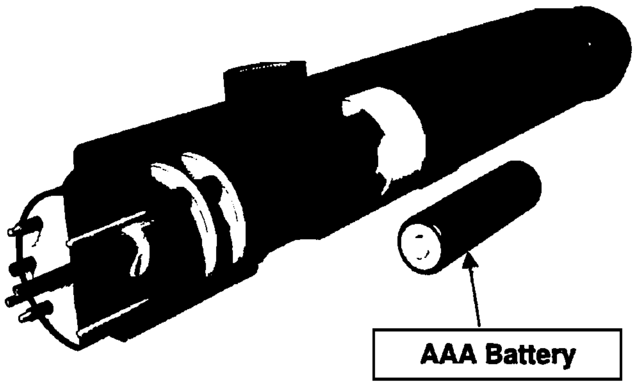

Figure 3. A cutaway design sketch for the ion traps held inside the vacuum tube

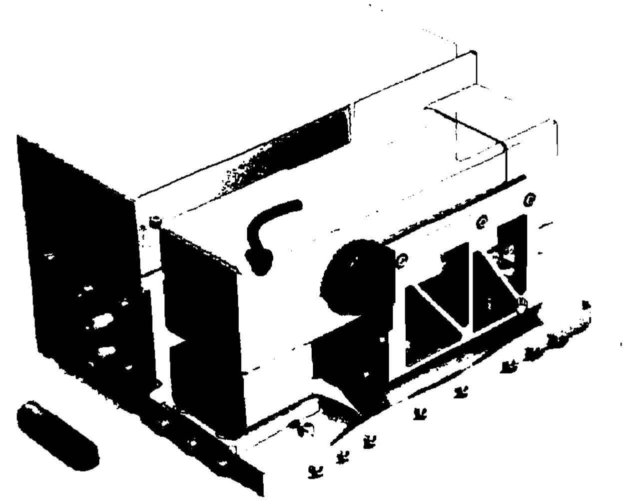

Figure 4. Design sketch for total 3-liter Ion clock package

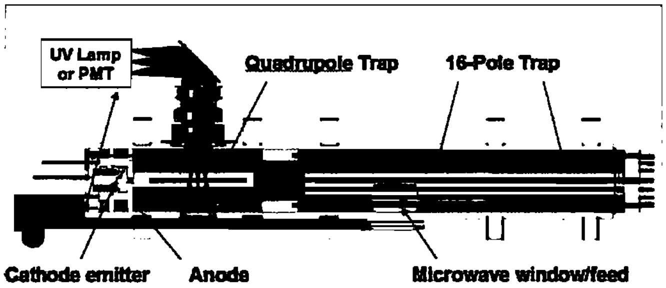

Figure 5. A cutaway view of trap assembly with an overlaid image of optical ray traces (blue) which show the UV optical pumping and detection methodology.

IV. QUANTUM LIMIT FOR MICROWAVE CLOCK OPERATION

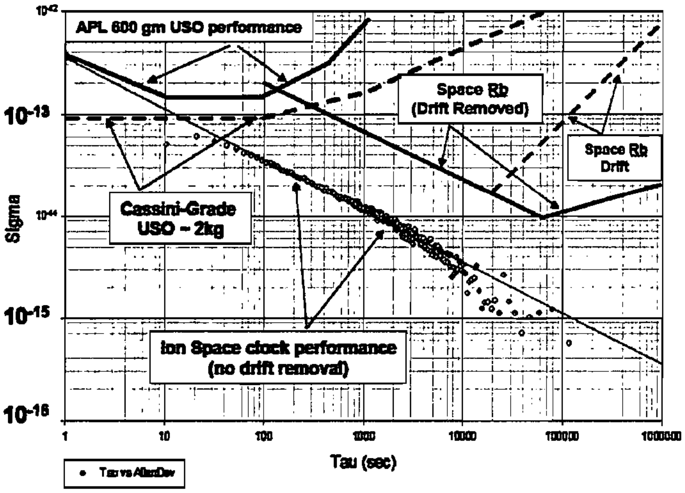

Figure 6. Breadboard ion clock measured Allan deviation for liter clock package. GPS space Rb is shown in red. Space USO quartz performance is also shown.

ACKNOWLEDGMENT

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