

Progress on Small Mercury Ion Clock for 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 $\sim 1\text{-}2 \times 10^{-13}$ 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 $1\text{-}2 \times 10^{-13}$ 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 over three 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 $\sim 400^\circ\text{C}$ 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.

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. Radio-science measurements with an ultra-stable on-board atomic clock will also be advanced dramatically. For example, a solar flyby to 10 solar radii would improve gravitation red-shift tests of relativity by 10,000-fold over those carried out by NASA with an H-maser sub-orbital launch in 1976 [1].

II. PLANETARY SCIENCE APPLICATIONS FOR ATOMIC CLOCKS

Several planetary measurements rely on ultra-stable atomic clocks, usually located in Earth based tracking stations. Two-way Doppler tracking of space-craft is capable of velocity resolution as good as $0.1 - 0.01$ mm/s. Ranging measurements are carried out to an accuracy of ~ 1 m [2-5]. An example of how these measurements can reveal planetary structure is illustrated in the figure below showing a planned gravity mapping of Jupiter in the JUNO mission.

The Doppler signal near close approach (perijove) shows velocity changes by 20 km/s and the velocity change from the J2 (lowest order departure from spherical planetary shape) is nearly 10 km/s [6]. J2 and several higher harmonics of the planetary mass distribution can thus be measured with very high precision with 0.1 mm/s Doppler sensitivity. This and all other deep-space missions are navigated via Doppler tracking and Ranging by use of ground based H-maser clocks referencing 2-way microwave navigation links. Clocks on-board solar system spacecraft will reduce the need for the $\sim 50\text{-}100$ kW uplink from DSN stations and allow nearly any radio astronomy antenna site to receive the stable 1-way downlink to navigate spacecraft.

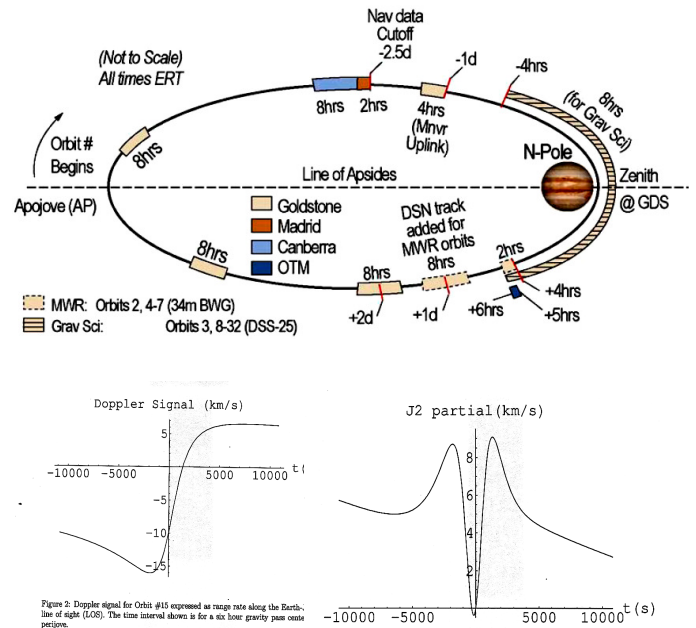


Figure 1: Proposed JUNO gravity mapping of Jupiter's interior. Spacecraft velocities are measured to 0.1 mm/s velocity resolution during the planetary flyby. Typical orbital velocity changes are as big as 10 km/s.

III. PHYSICS PACKAGE STATUS

The physics package is shown in figure 2. The mechanical package shown is designed to withstand generic random vibration levels of over $10 g_{rms}$. 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 [2].

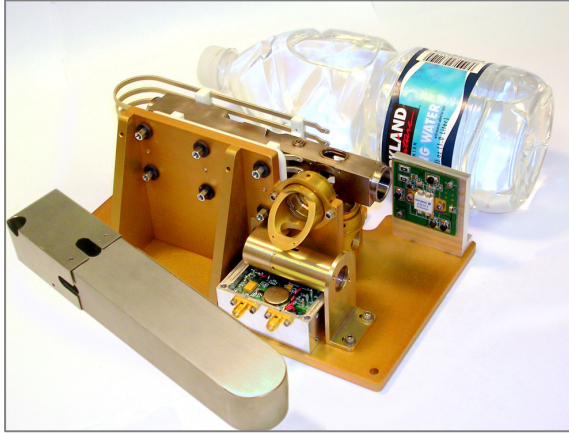
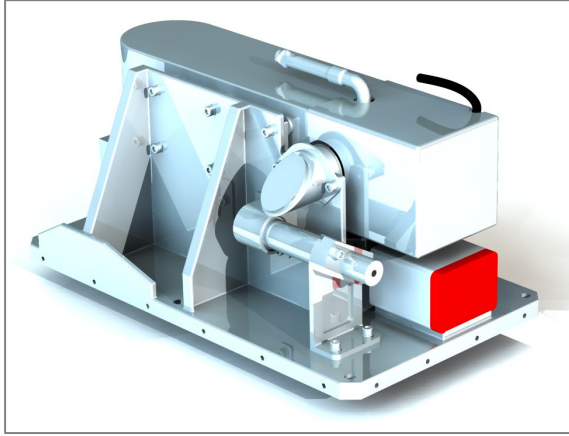


Figure 2. The ~ 3 liter physics package with baseplate, photomultiplier tube and vacuum tube mounting through the two layer magnetic shield. An outer magnetic shield is not shown. A liter bottle is also shown for scale.

IV. LAMP LIFETIME STRATEGIES

The ion clock relies on optical pumping to prepare and to detect the $^{199}\text{Hg}^+$ 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 2 turn coil to inductively excite a discharge inside. This is housed inside an oven held at about 60 C. Typically 10W is dissipated within the exciter circuit and bulb for bright mode operation. That is, about 5 W are dissipated within the lamp discharge. For in-vacuum space operation we have housed the lamp bulb in a package similar to the GPS Rubidium clock [7]. 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.

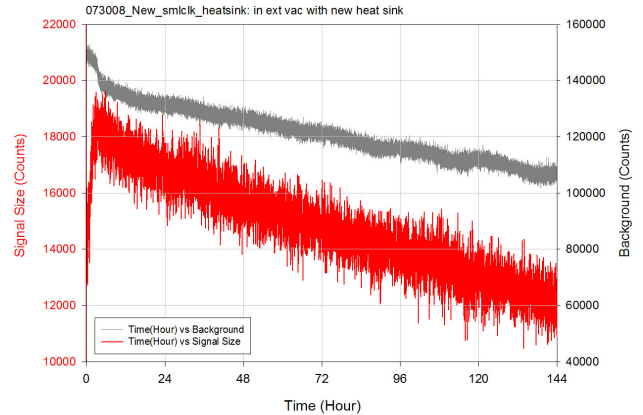
Under higher power operating conditions with previous exciter designs and long term field tests, where ~15 W are dissipated within the lamp discharge, lifetimes to ~ 4 years have been achieved. We expect the substantial power reduction within the discharge will increase the lifetime. Other bulb materials or wall coatings reduce the Hg reaction with the

fused silica bulb walls and will also lead to extended lifetimes [8-10].

V. OPTICAL SYSTEM CONTAMINATION IN SPACECRAFT VACUUM

The UV light output from the plasma lamp can interact with gases within the light path to create very reactive compounds that will coat the optical elements and rapidly degrade the 194 nm transmission. This only happens in partial vacuum conditions as might be found within the ion clock instrument or within the spacecraft outgassing environment. The UV transmission and signal size for the clock operated in a vacuum bell jar is shown below. The base pressure is ~ 10^{-4} Torr resulting from outgassing from wires, electronic circuit boards and electronic instrument modules also within the bell jar. The rapid degradation of both signal size (~8% per day) and lamp light output is shown in Figure 3a and is traced to a build-up on the output face of the lamp bulb. Since the 185 nm and 194 nm lines from the Hg lamp are both energetic enough to dissociate molecular oxygen and other organic molecules, an opaque layer accumulates and diminishes the UV output. This layer remains on the face even after the system is brought back to atmospheric pressure. It can be removed with an acetone or methanol surface wipe. When the lamp is operated in an ultra-high vacuum vessel, the light output does not diminish as rapidly and perhaps not at all.

(a)



(b)

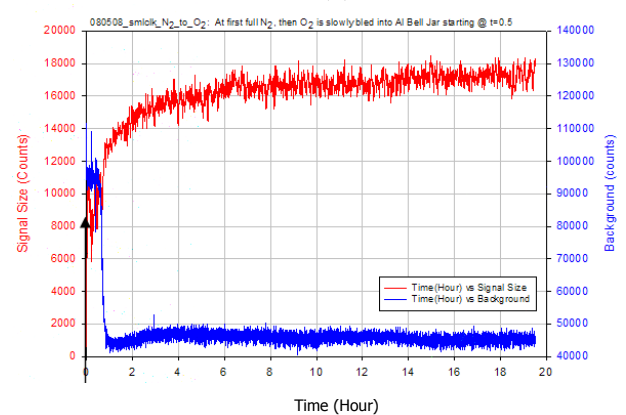


Figure 3. (a) UV light reduction as Hg lamp is operated in a bell jar vacuum where wires, electronic circuit boards, etc. outgas to hold base pressure to $\sim 10^{-4}$ Torr. The red trace shows Hg ion clock signal size. The grey trace shows direct lamp output. This degradation is from contamination buildup on the lamp face where 194 nm and 185 nm light dissociates background O_2 and other organic molecules. (b) The ion clock signal (shown in red) returns after O_2 is used to backfill the bell jar vacuum. At about 1 hour, O_2 is leaked into the system. Ozone and possibly atomic oxygen generated by the 194 nm and 185 nm lines then removes the contaminant buildup on the lamp face. The ozone formation in the oxygen rich atmosphere strongly attenuates the 254 nm UV line reducing the background light level as shown in the blue trace.

Figure 3(b) shows UV light output and signal size when an oxygen atmosphere is leaked into the bell jar after several day's degradation as described. The first hour shows the reduced signal size from deposits on the lamp face even though the system is backfilled with nitrogen gas to atmospheric pressure. At 1 hour molecular oxygen is leaked into the bell jar to atmospheric pressure (purging the N_2) and the signal size increases to the previous levels attained before the vacuum degradation occurred. Also shown is a dramatic decrease in the background light level, indicating ozone formation and consequent 254 nm absorption [11].

To prevent photochemical contamination of this kind, the optical system will be hermetically sealed with an inert gas backfill. Similar loss of UV light over time was seen in the Hg lamp used on the GP-B experiment [12] and photochemical contamination of all spacecraft with exposure to solar VUV light [13].

VI. SEALED TUBE LONGTERM LIFE TESTS

One of the most important simplifications and improvements of the physics package is the re-engineering of the vacuum tube used in the physics package of this clock. The re-engineered tube is designed and built from metals, ceramics and VUV optical windows to withstand a 400 C (or higher) temperature bakeout as is practiced in many modern electron tube technologies [14] SLAC Vacuum Tube website]. This eliminates the mechanical pumps used on the previous laboratory Hg clocks and allows integration into a much smaller physical package as shown in Figure 2. Also, this approach has eliminated consumables in clock operation since there is no flow-through of Hg as in previous ground Hg clocks and as in H-maser and Cesium clocks. It has saved power used to heat a HgO heater since no Hg regeneration is required.

As shown in Figure 4, the ion hold time inside the trap is dramatically higher than with a turbo pumped vacuum tube with window seals that cannot be safely baked above 200 C. Such systems can maintain ions within the trap for up to an hour, where ion losses stem from charge exchange with water vapor and other trace of complex molecules within the vacuum. In contrast, the 400 C baked and sealed tube with only getter pumping shows trap time of up to 5000 hours. A time record of the amplitude of the clock signal after ion loading has been halted and the electron emitter heater turn off at time zero hour is shown in Figure 4. The three longest trap times are 1000, 3000, and 5000 hours (to $1/e$ of initial ion signal) and are obtained for lower levels of the trapping rf fields. As seen in the figure, 340 V_{rms} on the trap electrodes, tends to hold ions for somewhat shorter periods, 500 hours or

so. The three long trapping times were measured over a 3 year period.

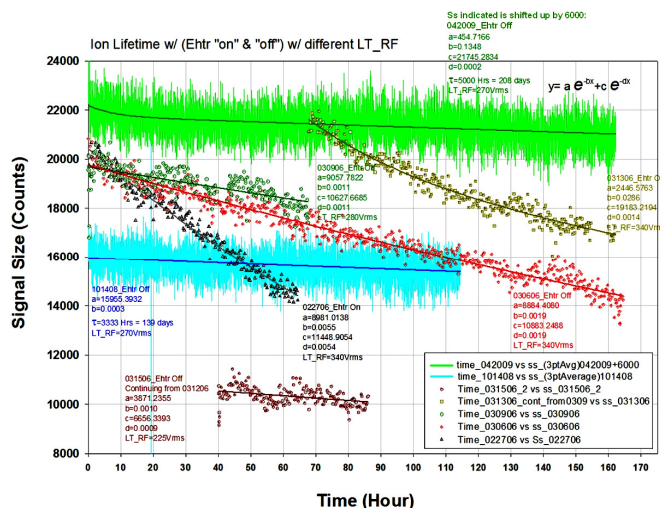


Figure 4. Ion lifetime within the quadrupole trap under different conditions. At relatively low rf voltage (~ 225 to 270 Vrms on single electrode, ~ 1.65 MHz) the trap time of 1000-5000 hrs is obtained. The higher voltages (~ 340 Vrms) tend to give shorter trapping times. The lowest displayed data set in brown was measured in March 2006, the blue data set measured in October 2008 and green data set in April 2009. In some cases the signal size at hour 0 has been offset to make data more easily viewed.

ACKNOWLEDGMENT

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