MINIATURIZED MERCURY ION CLOCK FOR ULTRA-STABLE DEEP SPACE APPLICATIONS

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Abstract

We have recently completed a prototype 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 ~2-3x10^{-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 1-2x 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 nearly 1.5 years with no measurable degradation of ion trapping lifetimes or clock short-term performance. Because the tube is sealed, the Hg source and Neon buffer gas are held indefinitely, for the life of the tube. There is no consumption of Hg in this system, unlike in a Cs beam tube where the lifetime is often limited by Cs depletion. 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 traditional 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 a several-hours averaging interval would enable one-way deep space navigations, where Doppler data are accumulated in a down-link only fashion. Currently, deep space navigation is implemented by measuring the Doppler frequency shift of a two-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.

For 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 feedthroughs, microwave windows, and UV optical windows often limit bake-out temperatures to 200 C. Nonmagnetic 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 UV grade sapphire windows can transmit at 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 bake-out, 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]**.

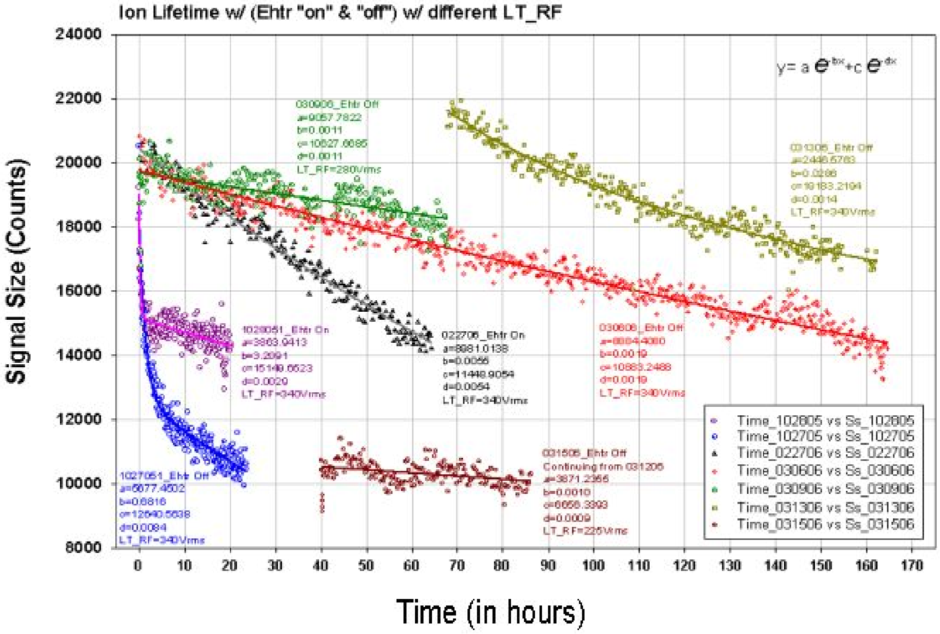

Figure 1. Ion trap times are determined by decay of the 40.5 GHz clock signal over time. The above span covers 170 hrs (~ 7 d). The time to 1/e of the initial signal size varied from 400-500 hours to 1000 hours.

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.

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 throughout the lifetime of clock operation.

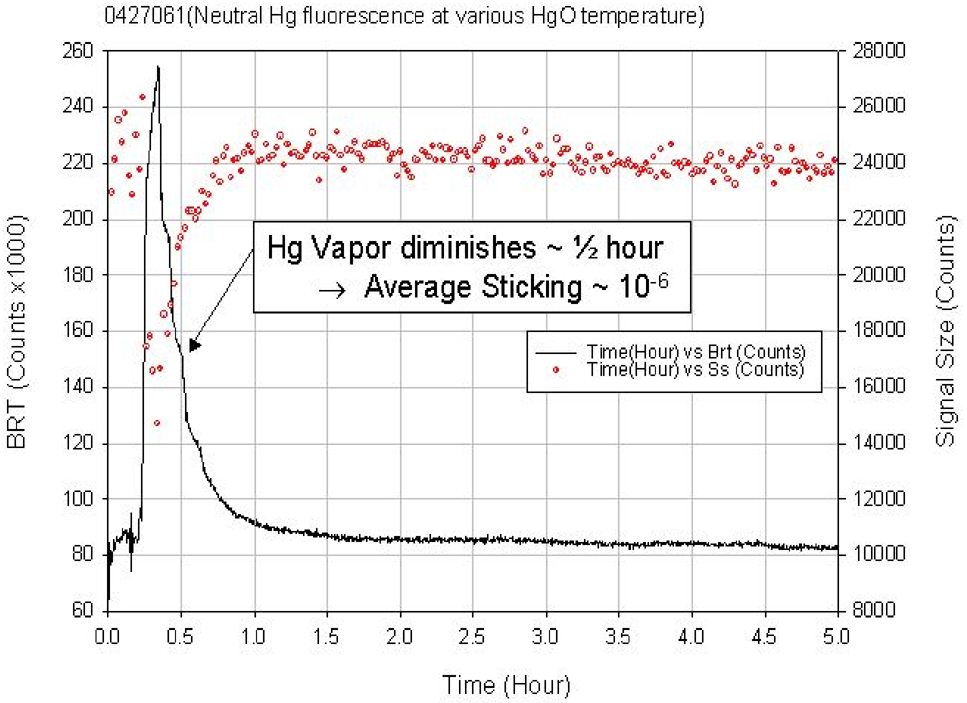

Figure 2. Simultaneous measurements of 194 nm fluorescence from trapped $^{199}Hg^+$ ions (red) and 185 nm neutral ^{199}Hg vapor (black). HgO oven is brought to ~ 270 C for ~ 1 minute at 0.25 hour. During the ~1/2 hour decay of the neutral vapor, the Hg atoms transit the liter-sized tube ~ 10^6 times, 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 2-3 liter total package volume. The physics package shown in Figure 3 occupies about 1 liter of the 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 prototype unit. Similarly, the clear area of the UV windows is equal to that of the prototype flange mounted windows.

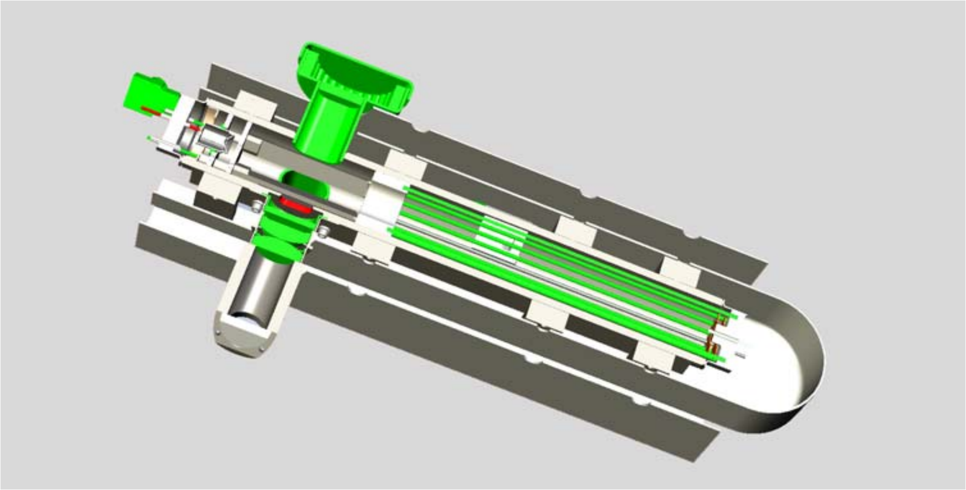

Figure 3. Cutaway design sketch for the 1-liter ion clock physics package layout. The ion tube with two layers of magnetic shielding occupies ~ ¼ of the package volume.

The package shown in Figure 3 is overlaid on the GPS IIF clock payload footprint in Figure 4 below. The dimensions shown are in inches.

IV. ELECTRONIC SUBSYSTEMS

Several electronic subassemblies are required to bring the physics package to a complete frequency reference. They are briefly described in this section and in Figure 7.

A. HG LAMP, EXCITER, AND OVEN

The Hg lamp is excited at about 200 MHz with a power oscillator circuit similar to the Rb lamp exciter/oven in the GPS Rb clock package. The lamp exciter is on for 2 seconds, and switched low (to a lower rf power dim state) for about 4 seconds during clock operation. Power required for operation is under 10 watts.

B. PHOTMULTIPLIER FLUORESCENCE DETECTION A/D

The low-level fluorescence from the ions is used to determine the frequency detuning of the USO oscillator from the reference atomic ion transition frequency. This module contains a UV sensitive photomultiplier tube, a dynode resistor chain, an analog to digital amplifier and discriminator chip, and a 1000 V power supply. Pulse counts of detected UV light will be relayed to a counter attached to the processor controller (below).

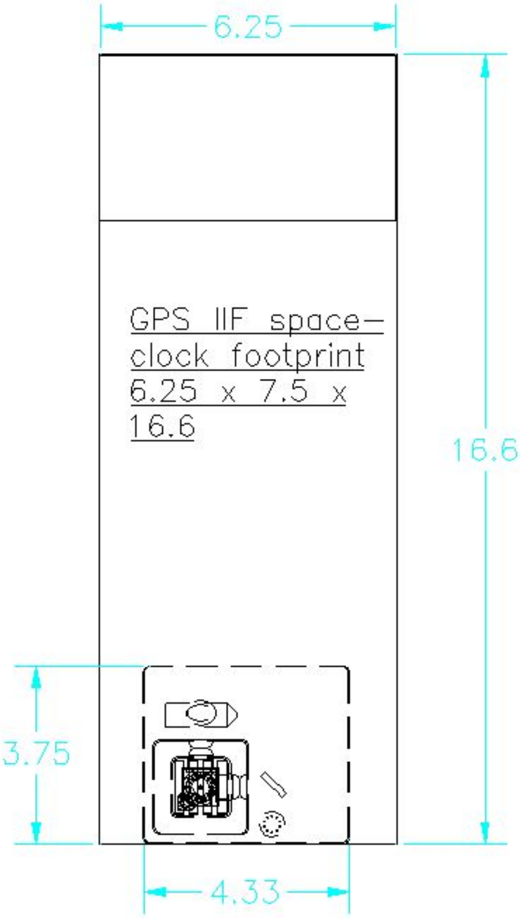

Figure 4. Two-liter Ion clock package size compared to the GPS clock payload platform.

C. ELECTRON EMITTER AND HEATER SUPPLY

The electron source is used to ionize neutral Hg atoms to form ions inside the trap. All deep spacecraft and Earth orbiting satellites have multiple traveling wave tube amplifiers to power the high frequency downlink.

D. C-FIELD COIL AND CURRENT SUPPLY

In order to separate the clock transition of $^{199}Hg^{+}$ ion from F=1,m=+-1, the Zeeman transition, a constant Helmholtz-fashioned DC magnetic field coil is used to supply approximately 50 mG reference B field primarily in the multipole region.

E. ION-TRAPPING RF/DC SUPPLIES

These electronic sub-assemblies are used for creating the trapping field by applying the rf voltages (2 - 3 MHz) to the quadrupole and the multipole trap electrodes. Low-voltage DC bias (~10 V) is applied to the endcap electrodes and to rf electrodes to shuttle the ions back and forth between the quadrupole and the multipole trap.

F. MICROWAVE MULTIPLIER CHAIN, SQUARE WAVE MODULATION AND TRACKING SYNTHESIZER

$^{199}Hg^{+}$ ion clock resonance frequency involves 40.5 GHz, derived from an ultra-stable oscillator (USO) through a series of multiplication and mixing. A lower 7 MHz synthesizer will make finer adjustments on 40.5 GHz to drive the clock transition while the ions are in the multipole trap.

G. HGO OVEN

A miniature heater element (a spot resistive heater, ~1 W) is attached to the appendage oven outside the trap assembly vacuum tube, which is heated to ~ 200 C to release Hg into the tube intermittently, if needed.

H. POWER-CONDITIONING MODULE

Stabilizes the voltage/current supplied to the instrument from the spacecraft power bus.

I. PROCESSOR CONTROLLER

This is a computer that handles the main clock operation, as well as collecting/analyzing data and communicating with other sub-systems for diagnosis and data transfer.

A digital operating system can reduce onboard electronics. The ion clock is controlled by a digital processor which generates a USO frequency estimate during each measurement cycle. The sequence of operations controlled by the processor is shown in Figure 5 and lasts about 5 seconds or so. To further reduce the mass, complexity, and power of the instrument, we need not voltage-steer the oscillator on board the s/c. Instead, the ion-clock frequency standard can operate in a listen-only mode with no voltage corrections applied to the USO control port. The sequence of digital center frequencies of the LO would remain in numerical form and be sent as telemetry to ground stations, where they could be applied to the received and digitized downlink of LO frequency variation. In this way, the free-running USO would be stabilized in the long term by applying the frequency error message sequence generated by the ion frequency standard.

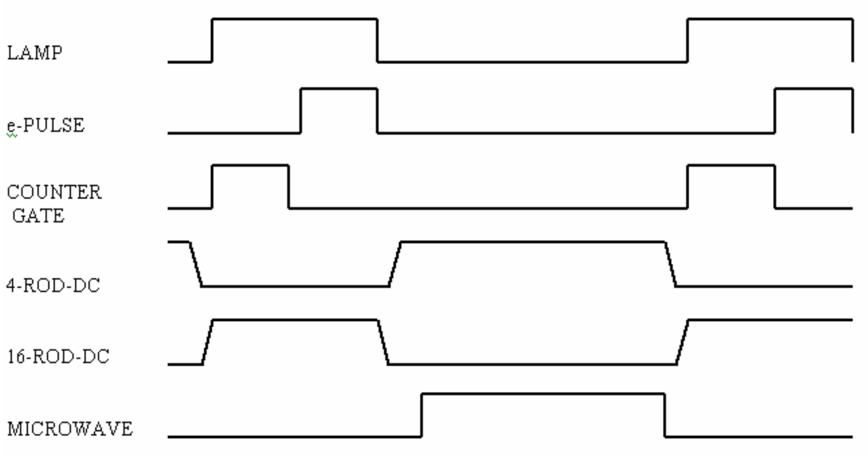

Figure 5. The processor-controlled sequence of operations used to measure local oscillator (LO) frequency.

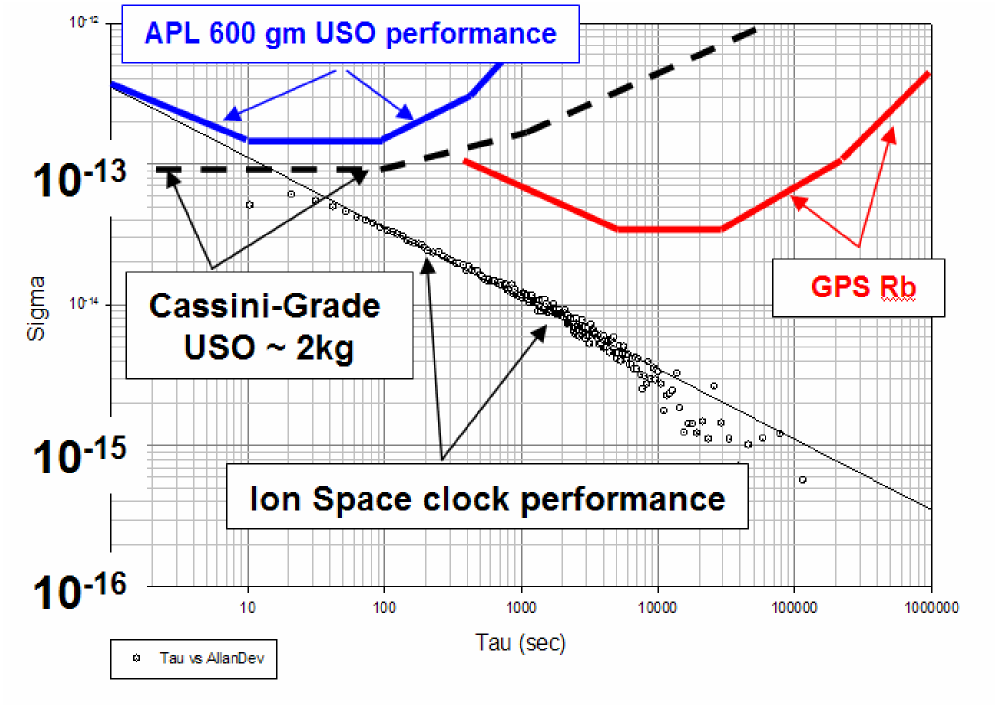

Figure 6. Prototype ion clock measured Allan deviation for liter clock package **[3]**. Also shown is performance of two deep space USOs **[4]**.

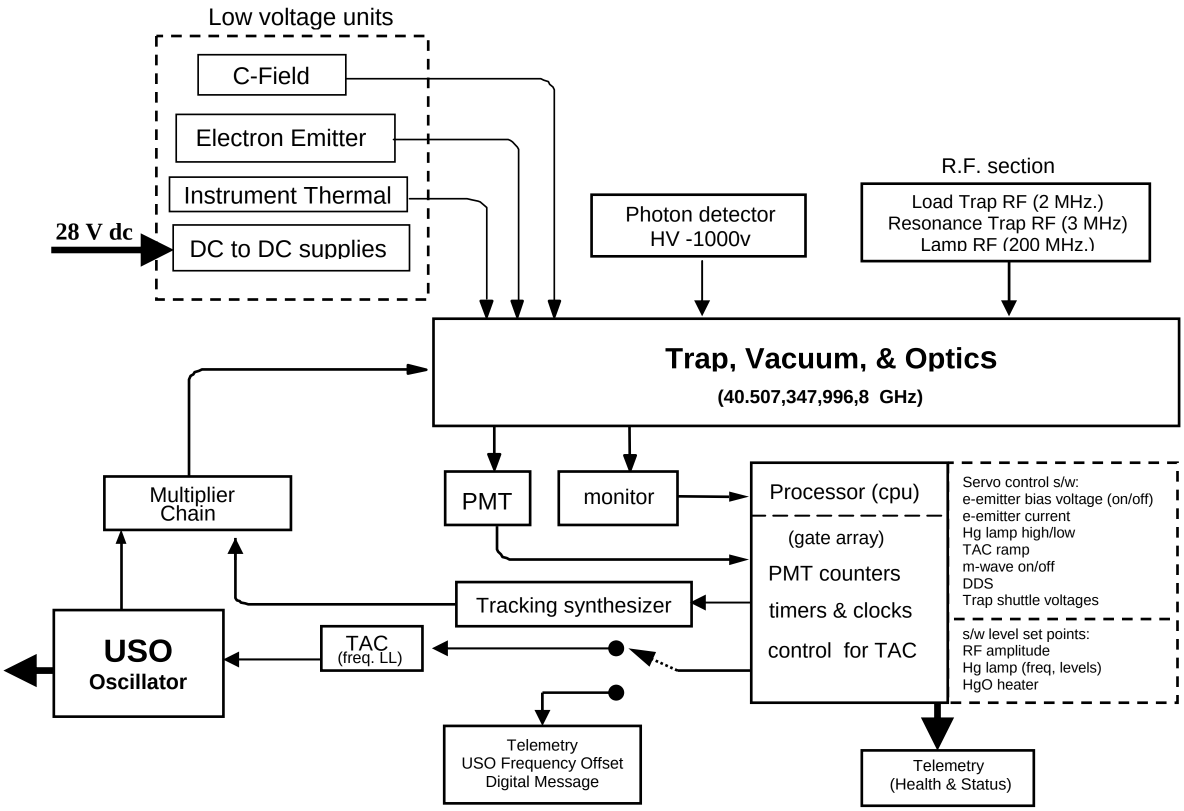

Figure 7. Electronic subsystems of $^{199}Hg^+$ ion clock.

V. ACKNOWLEDGMENTS

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