ONE-LITER ION CLOCK: NEW CAPABILITY FOR SPACEFLIGHT APPLICATIONS

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Abstract

We describe the development of a small Hg^+ ion clock suitable for space use. The breadboard physics package is 1-2 liters in volume, produces frequency stability of $10^{-13}/\sqrt{\tau}$, and should significantly advance the state of space-qualified atomic clocks.

INTRODUCTION

A space-based clock with frequency stability better than 10^{-14} over a several-day period would enable one-way deep space navigations, where Doppler data are accumulated in a downlink-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.

A clock with 10^{-14} or better frequency stability onboard a s/c could be used to navigate to the same precision as can be done with the two-way method **[1]**. Additionally, 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.

The short-term performance in the small atomic clock described here, $10^{-13}/\sqrt{\tau}$, can steer a s/c Ultra-Stable Oscillator (USO) reaching ~ 10^{-15} in a few hours averaging time, thereby supplying H-maser quality frequency stability in a much smaller package, 2-3 liters. Alternatively, this clock could be used to steer a 10^{-12}-grade quartz oscillator to exceed the typical performance of a USO beyond 100 seconds averaging and deliver a 10 to 100 times improved frequency stability over that of a USO at 1-hour averaging. This is because USO quartz oscillators typically show flicker frequency noise of ~ 10^{-13} from 1 second to longer times and show a linear frequency drift ~1-5 × 10^{-10} per day **[2]**.

There are many applications for ultra-stable clocks both in space and on the ground where a small package size is required. For example, there are severe restrictions on physical size for onboard instrumentation of deep space vehicles; total s/c mass (unfueled) is often less than 400 kg, with future trends toward even less mass. The components in a s/c radio system are 1-3 kg or less for each module. A USO is 3-4 kg, though most missions do not require one, and similarly, a Traveling Wave Tube Amplifier (TWTA) is about 2-3 kg.

Ion clock technology has shown great inherent stability, reaching ~ 3×10^{-16} frequency stability in a free-running mode where no periodic calibrations (of, for example, Zeeman transitions to determine internal magnetic fields and their changes over time) were made to disrupt continuous clock operation **[3]**. The design for the small clock discussed here is based on the same approach as used in the ion clock described previously **[3,4]**, though in a much smaller package.

Additionally, this technology has shown very small temperature coefficients, a few times 10^{-15} per degree C change. These numbers are measured without any thermal shielding of the clock physics and electronic packages. Only modest thermal shielding would be required to reach 10^{-15} stability.

CHALLENGES TO MINIATURIZATION

We have developed a relatively large laboratory $^{199}Hg^{+}$ trapped ion clock of exceptional performance, reaching frequency stability close to 3×10^{-16} at a few days averaging time **[3]**. The ion trapping methods developed for this clock are an essential element in reaching this stability. The liter clock ion trap is based on “ion-shuttling” between a linear-quadrupole and a linear-multipole as used in the ground clocks **[3-5]**. However, to meet the 1-2 liter size requirement, there will be changes and redesigns in the vacuum and optical systems.

The ground clock uses a turbo-molecular pump to maintain base pressures near 10^{-9} torr and to pump the helium buffer gas, maintained at the ~10^{-5} torr level. The helium buffer gas pressure is carefully regulated by a flow-thru temperature-controlled quartz leak, with an ionization gauge to measure system pressure and servo the temperature of the quartz leak to maintain a given helium level.

The liter clock will rely on getter pumping to maintain low vacuum base pressure. These getters will not pump noble buffer gases, so that no flow thru gas system will be required. This procedure will rely on very good cleaning and baking of the vacuum system before the vacuum is sealed off from the pump stand.

ION TRAP WITHOUT FASTENERS

The ion trap under development is shown below in Figure 1. The trap rods are brazed into the three Alumina rings on each end and at the junction between the quadrupole and 16 pole regions. The overall length is ~ 17 cm and the outside diameter ~ 1.5 cm. The inside diameter of the electrode circle is the same as used for the ground multipole clocks recently developed **[3-5]**. The purpose of the 16-pole extension is to prevent ion number variations from degrading the long-term clock stability to worse than ~ 10^{-15}. The extension also allows ions to be moved into a region that can be better shielded from the stray magnetic fields from the closely located electronics, e.g. the photomultiplier tube. The two rf trap regions will be driven at different frequencies to eliminate holes in the rf pseudo-potential near the junction **[4,5]**. The electrical interconnections between rf trapping rods operated at the same rf phase is accomplished by metallic plating on the ceramics where the rods are seated. The rods are made from molybdenum (non-magnetic) so that a narrow linewidth on the 40 GHz clock transition can be achieved. The stability goal requires Q ~ 10^{11} on this transition.

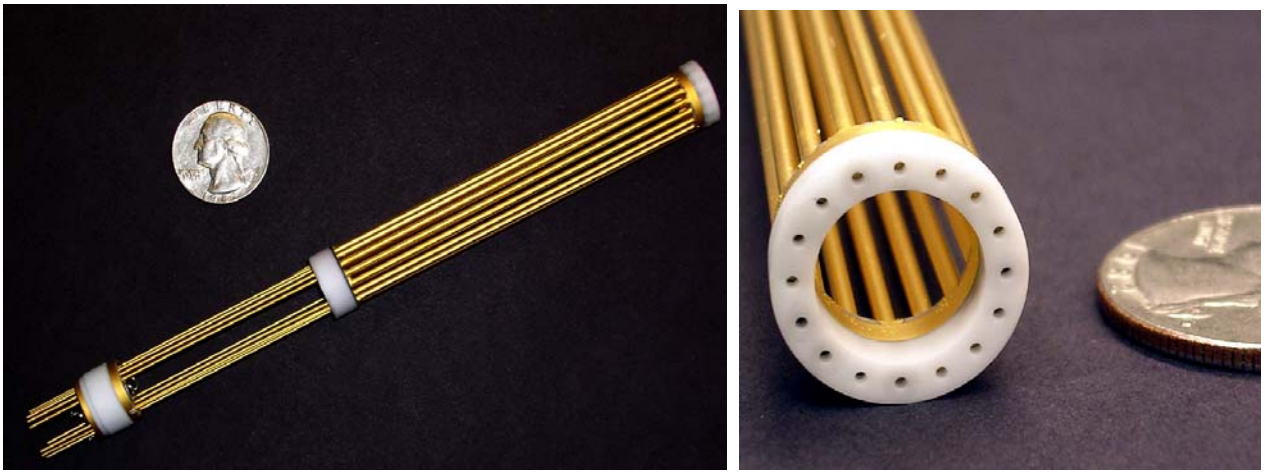

Figure 1. The monolithic ion trap used for the small ion clock. Optical state preparation is carried out in the tightly confining, open quadrupole on the left. Microwave clock spectroscopy is done in the loosely confining, closed 16-pole trap at right. Ions are electrically transported between the collinear traps.

OPTICAL SYSTEM

Collection of UV fluorescence from the trapped Hg ions is a critical element in reaching the short-term stability 10^{-13} at 1 second. We have designed and fabricated the system shown in Figures 2 and 3, comprised of two UV lenses and a folding mirror. Three identical systems are built, one for focusing the source light from a ^{202}Hg lamp onto the trapped ions and two more for collection of fluorescence from the ions. The dielectric-coated folding mirror serves as a dichroic reflector with > 95% reflectance for 194 nm ion fluorescence light and < 10% reflectance for the parasitic 254 nm light from a neutral Hg transition. Since stray light limits stability, it is important to eliminate the ~ 10× brighter 254 nm light from the beam, since it is within the detection band of the UV-sensitive PMT light sensor. These coated mirrors are off-the-shelf items and are much less expensive than the coated spherical mirrors previously used **[3,4]**.

The integration of this system with the ion trap assembly is shown in Figure 2. The housing that holds the lenses, mirrors, and detectors/source also holds the electronics modules used to operate the PMTs, pulse amplifier-discriminator, and discharge lamp. This single-module approach to the optical package is different from the ground clock of references **[3,4]**, where three independently moveable optics modules were adjusted to maximize ion fluorescence. The integrated optical system developed here can be aligned on the bench so that the foci of the three identical optical arms fall at the same position. The process of optical alignment is very important, since ray tracing was found not accurate enough to specify exact lens positioning. Again, this modular approach with pre-aligned optical components proved to be much more practical than the three separate spherical-mirror-based systems **[3-5]**.

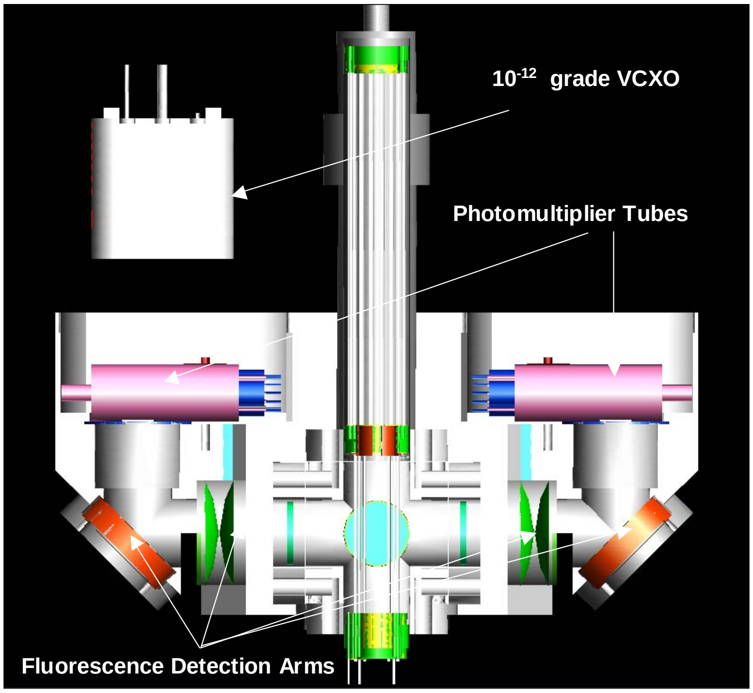

Figure 2. Cut-away view of the small ion trap and optics assembly.

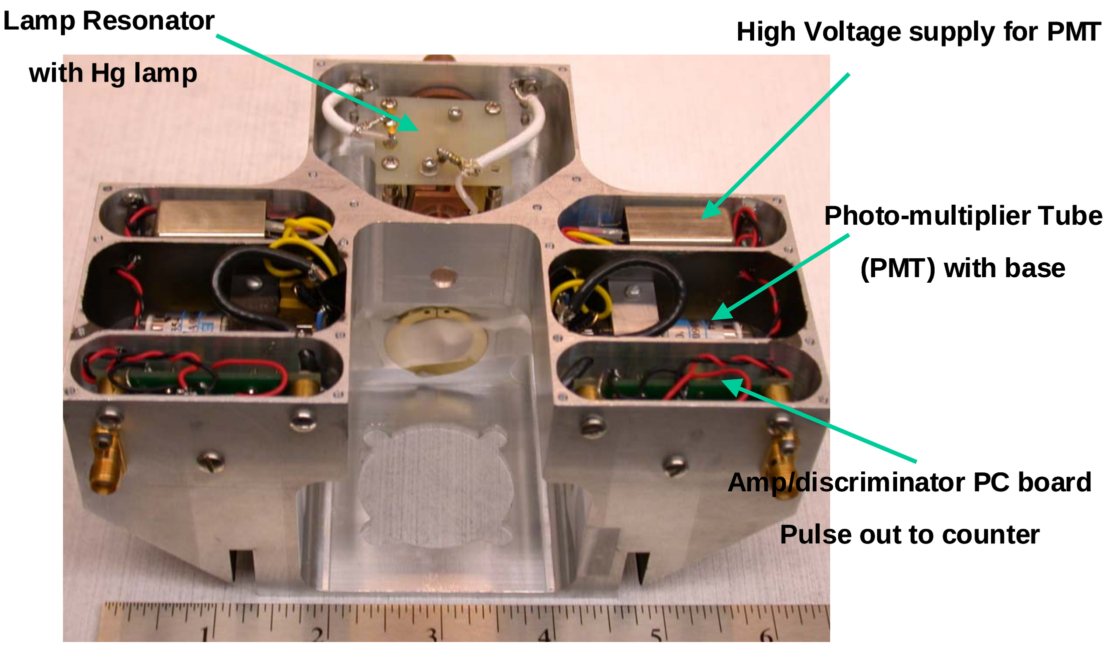

Figure 3. The assembled optics module contains three refractive optical systems, each focused on the same central point, where the "state selection" quadrupole ion trap will be centered.

FIRST OPERATION, $10^{-13}/\sqrt{\tau}$ SHORT-TERM STABILITY

Following bench-top optical alignment and vacuum system bake-out to ~ 150C for a few days, the optics module was mounted to the vacuum system cube (1.33") and ions were trapped. The 40 GHz resonance lines shown below were measured for ions in a quadrupole trap of the same dimensions as the quadrupole load trap of Figure 1. In addition, no magnetic shielding was used to shield ambient Earth's and proximity magnetic fields from the optics module electronics. Microwaves were propagated through the 45-degree- oriented folding mirrors in Figure 2.

The signal-to-noise ratio and line-Q for these resonances indicate excellent short-term Allan deviation, ~ $10^{-13}/\sqrt{\tau}$ (τ in seconds), as good as a generic H-maser short-term performance.

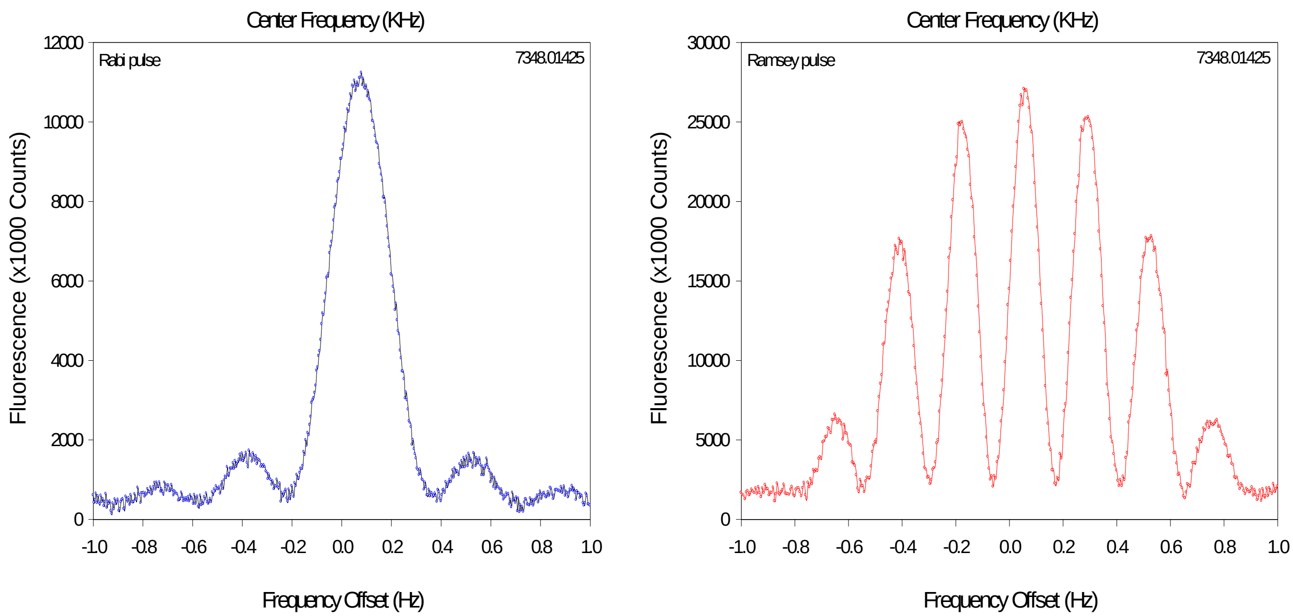

Figure 3. Typical resonance curves for clock transitions in the quadrupole load trap for the small ion clock. The Rabi single microwave pulse is performed with a 3-second interrogation interval. The Ramsey resonance on the right is made with two ~ 0.5 second pulses 5 seconds apart. The data plotted are UV fluorescent light collected in the PMTs (shown in Figures 2 and 3) vs. microwave frequency applied to the trapped ions.

SUMMARY

In a package that is over 10× smaller, we have demonstrated short-term H-maser stability in a breadboard Hg-ion space clock. Following this breadboard completion, more aggressive miniaturization and consolidation should produce an ultra-stable ion clock with very small mass, near 1 kg. There are several electronic modules that remain to be built, including the trap rf drivers, a field emitter electron voltage source, and a dc magnetic field supply.

The present size is largely determined by the trap, vacuum enclosure and the "perpendicularly" directed optical system. Even though several electronics modules remain to be fabricated, the 1-2 liter package seems very realistic, based on this first breadboard model.

ACKNOWLEDGMENTS

This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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QUESTIONS AND ANSWERS

BILL KLEPCZYNSKI (U.S. STATE DEPARTMENT): Just a quick question: What do you think you will get your power consumption down to, about?

JOHN PRESTAGE: It is going to be in the tens of watts. I don’t know exactly, 30 or so, maybe. I am not sure of that. Maybe they could tell me what is the bigger driver. I think at JPL the bigger driver is the mass and volume. I would take them to be the same thing.

It is going to be 30 or more watts. We are pushing just the physics now. But the physics looks very encouraging.