IPN Progress Report 42-155 November 15, 2003

A One-Liter Mercury Ion Clock for Space and Ground Applications

J. D. Prestage,[1] S. Chung,[1] T. Le,[1] M. Beach,[1] L. Maleki,[1] and R. L. Tjoelker[1]

We describe progress towards the development of a small mercury (Hg^+) ion clock suitable for space use. A small clock occupying a 1- to 2-liter volume and producing a stability of $10^{-12}/\sqrt{\tau}$ would significantly advance the state of space-qualified atomic clocks. Based on recent measurements, this technology should produce long-term stability as good as 10^{-15}.

I. Introduction

A space-based clock with frequency stability better than 10^{-13} over a several day period would enable one-way deep-space navigation in which Doppler data would be 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 and the coherent return link. Typically, these links are maintained for 7 to 8 hours per spacecraft track, requiring full use of a 34-meter antenna in the Deep Space Network (DSN) for the time the spacecraft is sufficiently above the horizon.

A clock onboard the spacecraft with 10^{-13} or better frequency stability could be used to navigate to the same precision as that which can be attained with the two-way method [1]. Additionally, when more than one spacecraft orbit the same planet and can be seen by a single antenna, the spacecraft can be tracked simultaneously with one antenna. Thus, this multiple-spacecraft tracking by a single antenna can reduce antenna usage and DSN costs.

The performance goal in the small atomic clock described here, $10^{-12}/\sqrt{\tau}$, will exceed the typical performance of a spacecraft ultra-stable oscillator (USO) beyond 100-second averaging and will deliver 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 $\sim 10^{-13}$ from 1 second to longer times and show a linear frequency drift of ~ 1 to 5×10^{-10} per day.[2]

Ion clock technology has shown great inherent stability, reaching $\sim 2 \times 10^{-16}$ frequency stability in a free-running mode where no periodic calibrations (of, for example, Zeeman transitions to deter-

---

[1] Tracking Systems and Applications Section.

[2] A. Kirk, personal communication, Jet Propulsion Laboratory, Pasadena, California, from Gravity Recovery and Climate Experiment (GRACE) flight oscillator pre-flight test data.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

mine internal magnetic fields and their changes over time) were made to disrupt continuous clock operation [2]. The design for the small clock discussed here will be based on the same architecture as used in the ion clock described previously in [2,3] although 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} clock stability.

II. Challenges to Miniaturization

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

We have developed a laboratory $^{199}\mathrm{Hg}^{+}$ trapped-ion clock of exceptional performance, reaching frequency stability close to 2×10^{-16} at an averaging time of a few days. The ion-trapping methods developed for this clock are an essential element in reaching this stability. The liter clock ion trap architecture will be based on "ion-shuttling" between a linear quadrupole and a linear multipole as used in the ground clocks [2–4]. However, to meet the 1- to 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 a $\sim 10^{-5}$-torr level. The helium buffer gas pressure is carefully regulated by a flow-through 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 no flow-through gas system will be required. This procedure will rely on very good cleaning and baking of the vacuum system before pinching the vacuum off from the pump stand.

III. Monolithic Ion Trap

The ion trap is shown in Fig. 1. The trap rods are brazed into the 3 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 is ~ 1.5 cm. The inside diameter of the electrode circle is the same as that used in the trap for the ground multipole clocks recently developed [2–4]. The two trap regions will be operated at different frequencies since that will eliminate holes in the rf pseudo-potential near the junction [3,4]. The electrical inter-connections of the rf trapping rods operated at the same rf phase will be accomplished by metallic plating on the ceramics where the rods are seated.

The rods are made from molybdenum (non-magnetic) so that a narrow line width on the 40-GHz clock transition can be achieved. The stability goal requires a quality factor (Q) of $\sim 10^{11}$ on this transition.

IV. Integrated Optical System

The optical system for collecting good ultraviolet (UV) fluorescence from the trapped Hg ions is a critical element in reaching the short-term stability goal. We have designed and fabricated the system

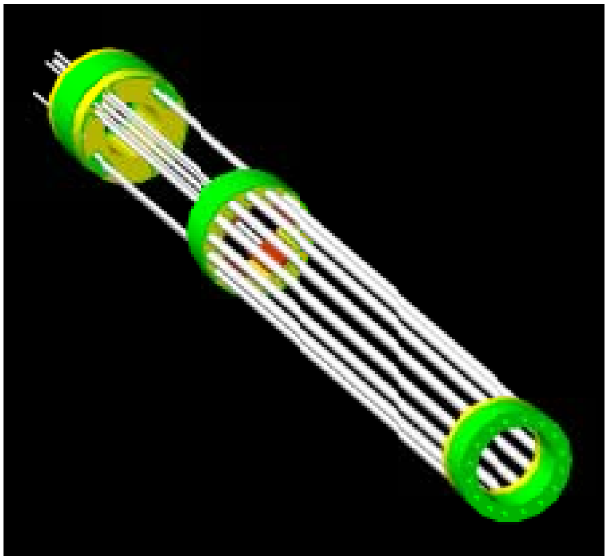

Fig. 1. The monolithic shuttle ion trap for the liter clock. Ions are optically state selected in the quadrupole, electrically shuttled to the 16-pole, where microwaves are applied to drive the clock transition, and then moved back into the quadrupole for state monitoring.

shown in Fig. 2; it is used both for focusing the source light from a ^{202}Hg lamp onto the trapped ions and for collecting fluorescence from the ions. The dielectric-coated folding mirror serves as a dichroic reflector with >95 percent reflectance for 194-nm ion fluorescent light and <10 percent reflectance for the parasitic 254-nm light from a neutral Hg transition. Since we are limited in stability by stray light, it is important to eliminate the ~10× brighter 254-nm light from the beam because it is within the detection band of the UV-sensitive photomultiplier tube (PMT) light sensor.

The integration of this system with the ion trap assembly is shown in Figs. 3(a) and 3(b). The housing that holds the lens, mirrors, and detectors/source also holds the electronics modules that operate the PMTs, pulse amplifier–discriminator, and discharge lamp. This is shown in the figure. This single-module approach to the optical package is different from the ground clock of [2,3], 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 just now under way, since we have recently completed the fabrication and assembly of the optical package.

V. Continued Work

There are several electronic modules that remain to be built, including the trap rf drivers, a field emitter electron voltage source, a dc magnetic field supply, magnetic shields, a multiplier chain from the local oscillator (LO) to 40 GHz. The microwave window is a ceramic vacuum break in the 16-pole trap region vacuum jacket so that conventional waveguide components will be used, all outside the vacuum.

The package 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- to 2-liter package seems very realistic in this first engineering model.

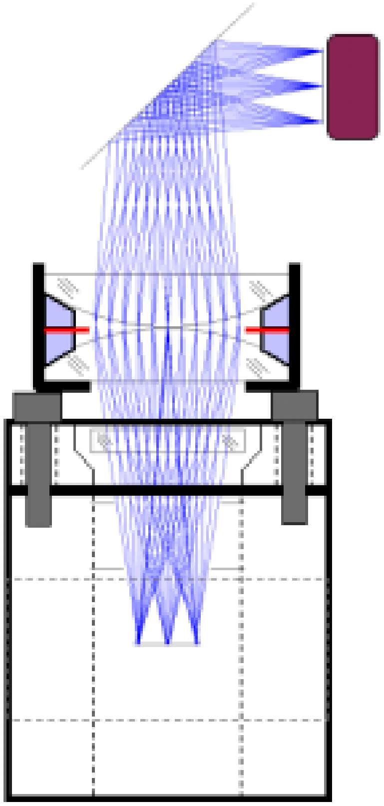

Fig. 2. UV optical system for state selection of the trapped ions. A dichroic folding mirror filters away the parasitic 254-nm light leaving the 194-nm Hg ion state-selecting light. The 34-mm vacuum cube and window flange are also shown.

References

[1] S. Bhaskaran, "The Application of Noncoherent Doppler Data Types for Deep Space Navigation," *The Telecommunications and Data Acquisition Progress Report 42-121, January–March 1995,* Jet Propulsion Laboratory, Pasadena, California, pp. 54–65, May 15, 1995.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-121/121B.pdf

[2] R. L. Tjoelker, J. D. Prestage, P. Koppang, and T. Swanson, "Stability Measurements of a JPL Multi-Pole Mercury Trapped Ion Frequency Standard at the USNO," 2003 Joint Meeting EFTF and IEEE IFCS, Tampa, Florida, May 2003.

[3] J. D. Prestage, S. Chung, E. Burt, L. Maleki, and R. L. Tjoelker, "Stability Measurements between Hg^+ LITE 12-Pole Clocks," *2002 IEEE IFCS,* New Orleans, Louisiana, pp. 459–462, May 2002.

[4] J. D. Prestage, R. L. Tjoelker, and L. Maleki, "Mercury Ion Clock Based on Linear Multipole Ion Trap," *2000 IEEE IFCS,* Kansas City, Missouri, pp. 706–710, June 2000.

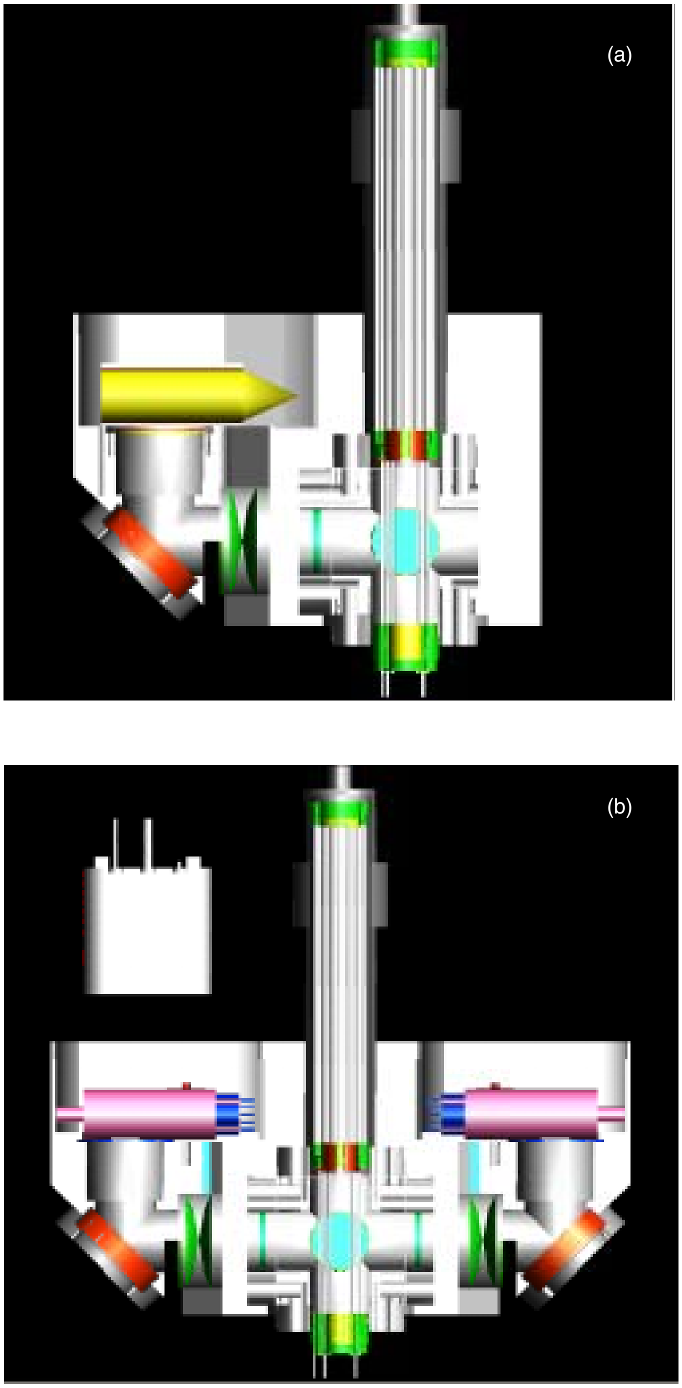

Fig. 3. A cross-section view of the optical package showing (a) the source optical arm together with the discharge lamp at the focal plane (the overall vertical length is 20 cm) and (b) the detection optical arms with a PMT at each focal plane. An ovenized quartz voltage-controlled crystal oscillator (VCXO) of adequate performance to meet the stability goal is shown in the upper left (the overall length is under 20 cm).