MERCURY ATOMIC FREQUENCY STANDARDS FOR SPACE BASED NAVIGATION AND TIMEKEEPING[1]

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Abstract

A low power Mercury Atomic Frequency Standard (MAFS) has been developed and demonstrated on the path towards future space clock applications. A self-contained mercury ion breadboard clock - emulating flight clock interfaces, steering a USO local oscillator, and consuming ~40 Watts - has been operating at JPL for more than a year. This complete, modular ion clock instrument demonstrates that key GNSS size, weight, and power (SWaP) requirements can be achieved while still maintaining short and long term performance demonstrated in previous ground ion clocks. The MAFS breadboard serves as a flexible platform for optimizing further space clock development and guides engineering model design trades towards fabrication of an ion clock for space flight.

INTRODUCTION

Atomic clocks are a cornerstone of space navigation. They provide an accurate time reference for absolute spacecraft ranging, highly precise and stable frequency references for spacecraft Doppler tracking, and low phase noise references enabling ΔVLBI and delta Differential One-way Range (ΔDOR) measurements **[1]**. To date, the most significant application of space based atomic clocks are in Global Navigation Satellite Systems (GNSS). The United States GPS constellation, fully operational in 1995, together with GLONASS, GALILEO, and COMPASS now collectively are flying more than 60 GNSS satellites. Each of these satellites relies on qualified atomic frequency standards to generate timekeeping signals in space.

While extremely high frequency/time accuracy and stability is achieved on the ground with a number of different atomic frequency standard (AFS) technologies, only a subset of these is suitable to the constraints of spaceflight. To date all GNSS atomic clocks have been based on one of three atomic clock technologies: Rubidium microwave cells, Cesium atomic beams, and Hydrogen Masers. In addition to the need for high reliability and minimal Size, Weight, and Power (SWaP), GNSS clocks must also withstand significant environmental stresses. These include vibration and shock, thermal and magnetic variations in orbit, and radiation effects.

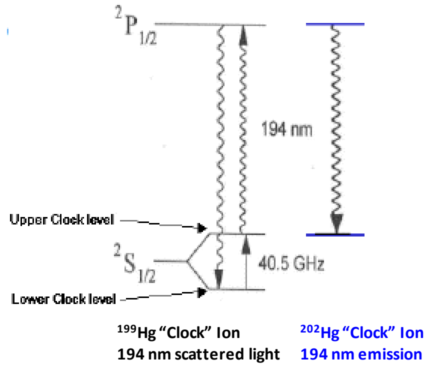

Figure 1. Mercury ion clock transition and UV transition for state selection/detection.

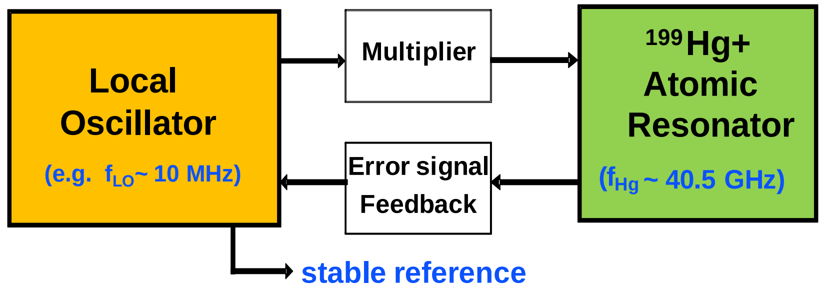

Figure 2. Mercury ion clock disciplining a Local Oscillator.

MERCURY ATOMIC FREQUENCY STANDARD (MAFS) FOR GNSS

Mercury ion clocks based on the ground state hyperfine transition in trapped ^{199}Hg ions are a promising technology for an operational space clock that simultaneously addresses reliability, SWaP, and stability performance requirements. Trapped ions are easy to handle in a microgravity environment, and the 40.5 GHz hyperfine transition (Figure 1) is the highest frequency and least magnetically sensitive of the alkali-like atoms and ions that have been investigated for atomic clock applications. Room temperature, lamp-based mercury quadrupole and multi-pole linear ion trap based frequency standards have been highly developed for ground applications resulting in three generations of reliable and continuously operating mercury ion frequency standards with good accuracy and very high stability **[2-7]**. While funding to develop a mercury ion clock for GNSS a decade ago **[8]** was not sustainable, mercury ion clock technology advancements have continued to be made within several NASA programs. Multi-pole **[4]** and compensated multi-pole ion traps **[6]** have proved to effectively eliminate residual ion number sensitivity, resulting in UTC level timescale demonstration with a single mercury ion trap standard having long term frequency variation at the low 10^{-17} level per day **[5,7]**. NASA technology efforts continued small ion trap development **[9]** and very long ion trap lifetimes have been obtained in a getter pumped vacuum assembly designed to be baked to 450 °C and stable signal-to-noise has been demonstrated over several years **[10]**. Long term stability and environmental sensitivity in this high temperature bake-out ion trap assembly has yet to be characterized, though operation with only a sealed getter pump evacuating a larger multi-pole ion trap assembly baked to 200 °C has demonstrated very stable clock operation over 9 months **[11]**. These continued NASA/JPL advances in ultra-stable timekeeping and small ion trap "vacuum tube" technology have positioned the mercury ion technology for a renewed effort towards realizing a GNSS capable mercury ion frequency standard.

In 2008, NASA's Jet Propulsion Laboratory (JPL) and Symmetricom teamed to advance Mercury Atomic Frequency Standard (MAFS) development towards future GNSS application. The development path involves maturing a mercury ion clock through breadboard, prototype, and engineering model phases meeting specific GNSS SWaP, stability, and performance goals. In this proceeding, we describe a 2010 demonstration of the first complete low power MAFS ion clock in a Local Oscillator, power, and clock control configuration appropriate for spaceflight.

MAFS BREADBOARD DEVELOPMENT

Mercury ion clocks developed at JPL are passive frequency standards (Figure 2): the ions are used to steer the local oscillator (LO). The stability of the frequency output of the clock for time intervals less than one day is highly dependent on the quality of the LO (Figure 3). The optimum stability performance of the ion clock for time intervals less than ~10,000 seconds is inversely proportional to SNR*Q*$\tau^{1/2}$ (where SNR is the achieved Signal-to-Noise Ratio in a 1 Hz bandwidth for a single interrogation, Q is the atomic line resolution, and τ is the averaging interval). Since the Q is inversely proportional to the clock transition interrogation time, short term LO stability limits the practical clock interrogation cycle for a specific implementation. In the laboratory there exist several LO options such as a cryogenic oscillator or hydrogen maser, but for spaceflight we are currently restricted to using a quartz-based LO. The first mercury ion clock implemented at JPL was able to control all three LO's with mercury ions confined in a quadrupole ion trap assembly [3] with the performance dependent on the LO implementation (Figure 3). While the ion cloud size in the quadrupole ion trap was small (~2 mm diameter by ~7 cm long), the surrounding vacuum/optics/magnetic system were built with larger vacuum system, optics, and electronic components. The entire ion clock required 2 racks of space and more than 1 kW of power. Four of these standards disciplining quartz LO's were developed and several years of operational experience was obtained in JPL's Frequency Standards Test Laboratory and at remote sites in NASA's Deep Space Network.

A space ion clock for GNSS application must consume less than ~30W, fit in a volume of a few liters, have simplified external interfaces, and be very reliable. A space ion clock configuration block diagram is shown in Figure 4. The ion trap/vacuum tube assembly, optical assemblies, ion trap electronics, USO/microwave multiplier, and clock controller subsystems form the complete instrument. We emulate a spacecraft interface with a single dc power input, telemetry line, and a 10 MHz reference output disciplined to the ~40.5 GHz "clock" transition.

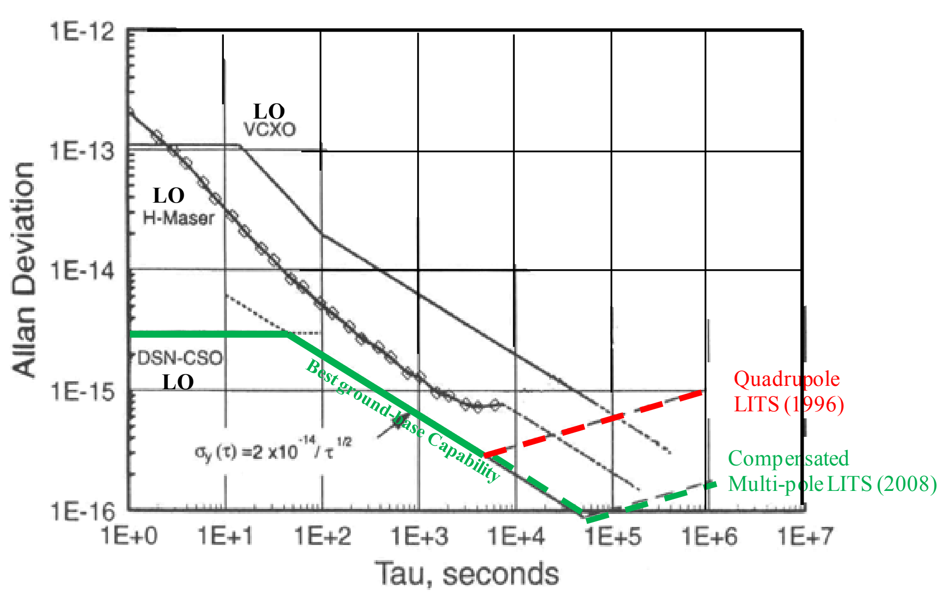

Figure 3. Represented mercury ion clock fractional frequency stability with different Local Oscillators. Space clocks are currently limited to using a VCXO as the LO (adapted from **[3]**).

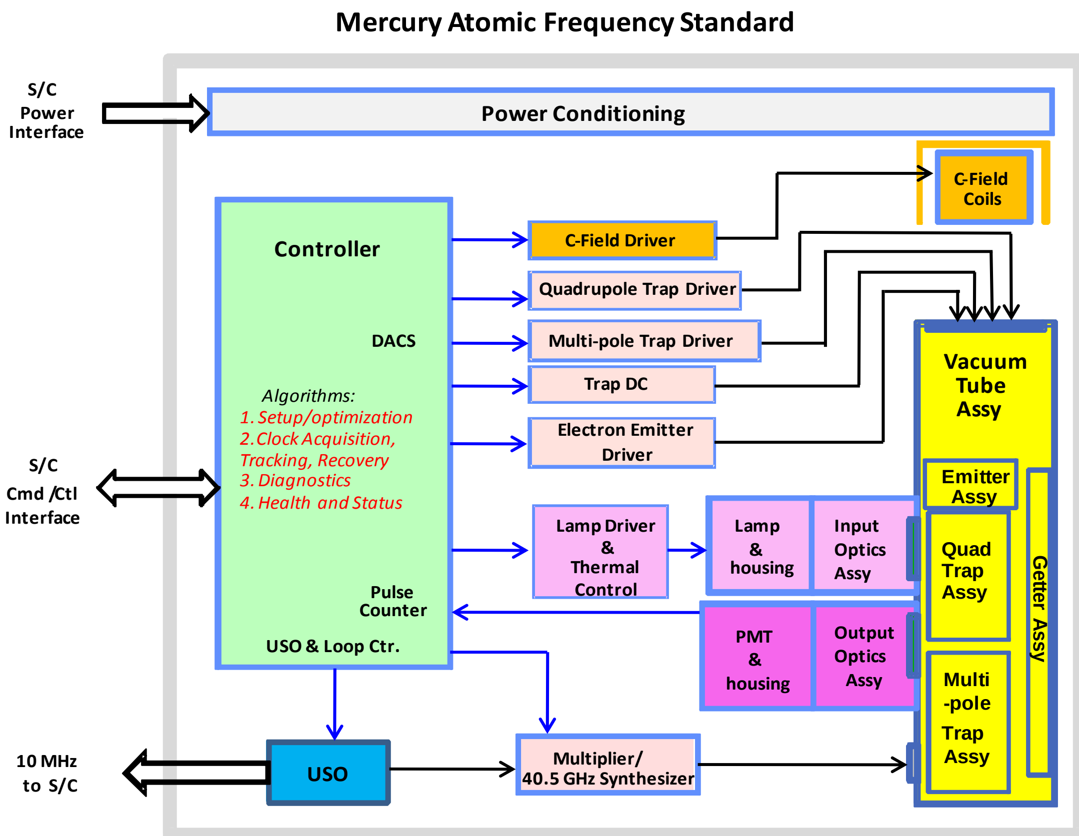

Figure 4. Mercury ion clock block diagram for an instrument configured for space operation. The only spacecraft interfaces are power, telemetry, and a stabilized frequency output from the USO.

We have developed a MAFS breadboard clock (Figure 5) to optimize the operating paradigm and guide engineering model design tradeoffs. All subsystems have been redesigned with a focus on reduced power, dc operation, reduced part count, and an identification of space-qualifiable part paths. The breadboard instrument has reduced ion clock power from ~1 kW to ~40W on a path to achieve our 28 Watt GNSS Engineering Model goal. The MAFS breadboard clock contains a commercial high performance USO disciplined in a frequency lock loop similar to prior implementations **[3]**.

The MAFS breadboard ion clock was initially operated with an available quadrupole ion trap assembly. Nearly all components shown in Figure 5 were designed for GNSS appropriateness. While only a brief summary is possible here, some of the recent developments include:

- Low power ion trap RF sources at 3.3 MHz and 1.4 MHz and high Q resonant circuitry to build up needed ion trapping potentials.

- Low power RF discharge lamp driver circuitry built up with a self sustaining oscillator approach. This simplifies lamp starting and clock operation between two different lamp discharge states. The new circuitry was also capable of driving the lamp tank circuit with additional lead capacitance so that the driving circuitry can reside outside of a hermetically sealed lamp region.

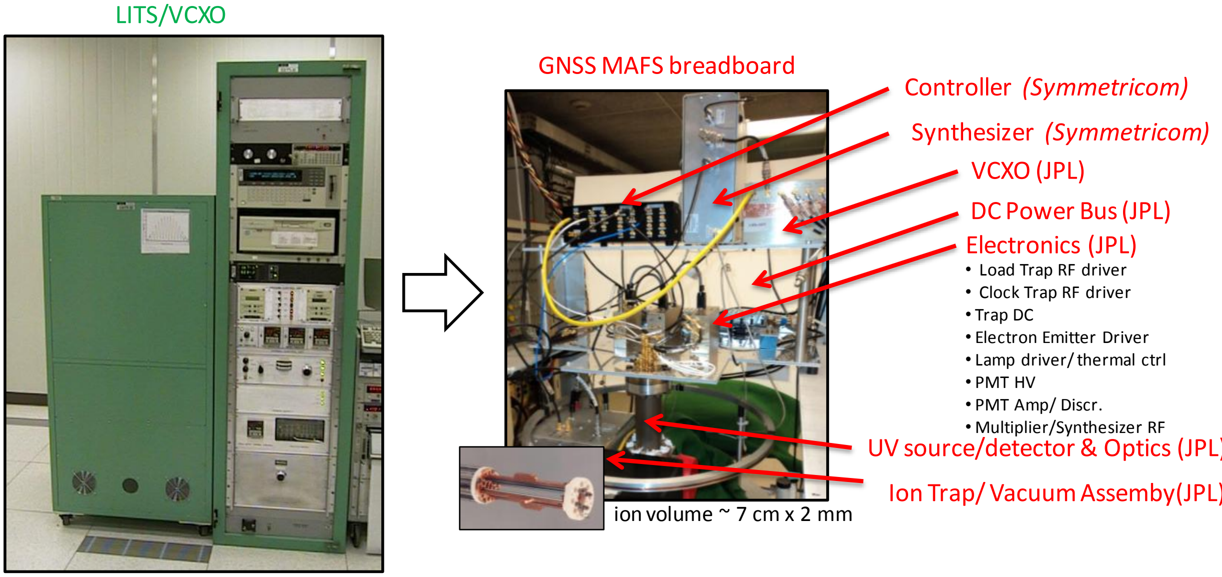

Figure 5. a) Implemented mercury ion clock based on a Linear Ion Trap and quartz LO **[3]**. b) Low power ion clock in a spacecraft interface configuration steering a quartz USO from a digital controller designed for GNSS operation.

- Steering the quartz LO is a challenge as it is disciplined in a relatively slow frequency lock loop. For long life clock operation a large VCXO control range is required with high precision. A Time-Analog-Conversion approach implemented on prior ground implementations **[13]** has been replaced with a high resolution DAC approach implemented in the new digital controller.

- The 40.5 GHz synthesizer used on prior implementations was built around a Step-Recover-Diode (SRD) approach that is an inexpensive and very stable. However, SRDs are notoriously sensitive to thermal/power instability and not favorable for spaceflight environments. For the MAFS breadboard a Dielectric-Resonator-Oscillator (DRO) approach similar to those used in other GPS clock applications was implemented. Stability tests of the SRD and the DRO approaches are shown in Figure 6. The DRO circuit produces higher power than the SRD approach which facilitates automated startup of the instrument and could prove advantageous if Zeeman line interrogation to stabilize the magnetic field environment at the clock is implemented. The DRO synthesizer/multiplier system has low noise and low spurious signal content. As seen in Figure 6, while not as stable as the SRD approach, the performance is more than adequate to support the typical ion clock stability when operating with quartz LO.

- The controller architecture is based on FPGAs that have a path to flight application. For breadboard demonstration, all controller functions were packaged in a single module shown in Figure 5. The controller was developed using parts with a radiation hardening path appropriate to GNSS application. Our philosophy was to incorporate as many clock activities/functions into the digital controller as possible without compromising required clock performance. The controller provides three key functions 1) sequencing ion loading, state selection, and microwave clock interrogation activities, 2) servo control of a few clock subsystems including steering the LO to keep it on frequency, and 3) telemetry monitoring of a prioritized subset of health/optimization monitor points. Each of these functions had previously been carried out with combination of commercial controllers, synthesizers, and counters. Currently a synthesized high-resolution DAC architecture provides 28 bits to steer the LO to accommodate existing flight USO designs. In general though, because flight hardened DACs are expensive and consume significant power, we strived to minimize their use. The highest priority telemetry to monitor clock health is collected and made available to the spacecraft. The 1.4 and 3.3 MHz trapping potential frequencies were also synthesized by the controller as well as the high resolution digital synthesizer to control the multiplier and clock tracking circuitry.

- For the breadboard demonstration, we used an available high performance commercial USO.

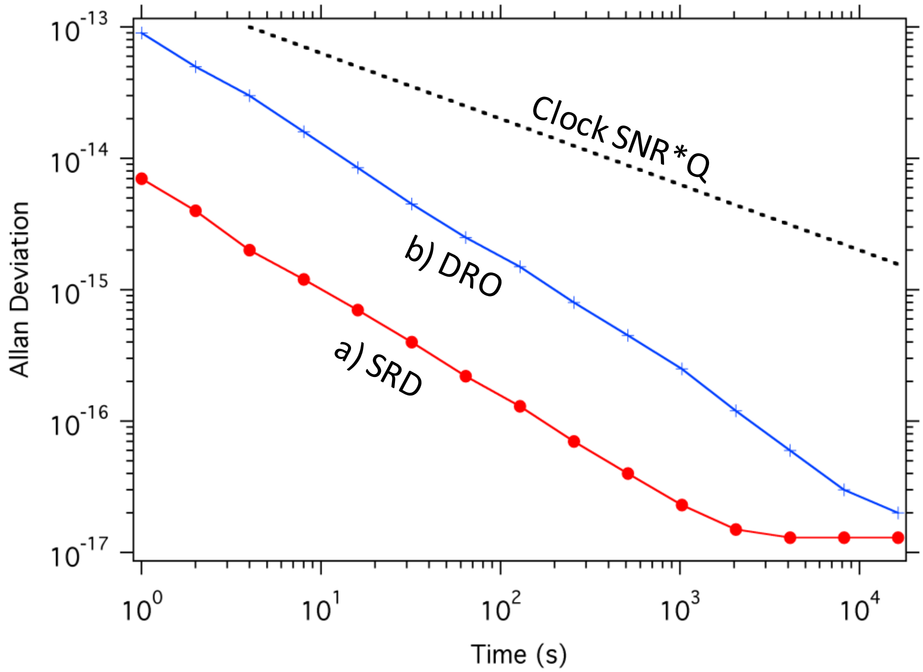

Figure 6. 40.5 GHz multiplier/synthesis approaches. a) a simple, low cost SRD approach used on prior ion clocks, b) a DRO based approach providing higher power and acceptable flight qualification path.

MAFS LO ACQUISITION AND CLOCK PERFORMANCE

For initial testing of the MAFS ion clock, while waiting for fabrication of a small, hardened multi-pole ion trap/vacuum tube assembly, we utilized a pre-existing four rod, quadrupole ion trap. The quadrupole ion trap volume itself is small, but the apparatus shown in Figure 5 was built up from modular conflat flanges and windows that could be baked to only 200 °C. The sealed vacuum system was evacuated with only a getter pump, charged with mercury, and backfilled with ~10^{-6} torr of Neon buffer gas in the spring of 2010. The modular DC powered electronics and new controller were designed to operate with existing (large and small) ion trap assemblies/physics packages including an individual quadrupole trap or a quadrupole/multi-pole shuttling trap architecture. (E.g., the MAFS breadboard is designed to accommodate the small, hardened ion trap/tube assembly shown in Figure 11.)

Acquisition of the MAFS clock signal from a cold start up requires capturing the quartz oscillator which can initially be at an unknown frequency far from the ion “clock” resonance. In prior ground implementations this capture was accomplished by slewing the LO frequency and measuring it against a calibrated hydrogen maser. When the multiplied LO output was within the ion clock capture bandwidth (atomic line Q) the loop was manually closed. To automate this procedure, in the MAFS breadboard demonstration the atomic line was initially broadened by applying a short, high power microwave pulse achieved with the new DRO based synthesizer. Fluorescence detected from the resulting broadened atomic line can then be detected with the USO far off frequency. In an iterative process the line is then narrowed by increasing the microwave pulse duration (narrowing the line) and decreasing the applied microwave power. Figure 7 shows a demonstration of the system's ability to capture the USO when an intentional $2x10^{-10}$ LO frequency step is introduced. The capture response is shown using two different gains. This will be further optimized, but demonstrates improved operability in both initial clock start up and potential recovery scenarios in the event USO lock is lost.

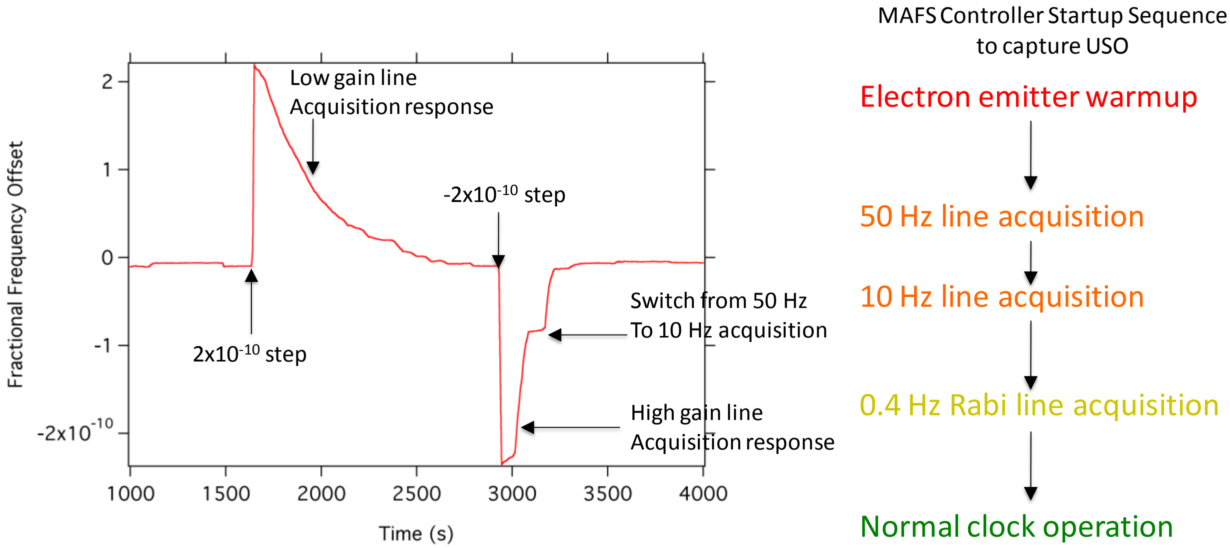

Figure 7. Demonstration of automatic acquisition of the ion transition with the USO LO.

Once the VCXO LO is on frequency, the narrow atomic clock transition is detected using Rabi interrogation. Figure 8 shows the 40.5 GHz clock resonance resulting from a 3 Hz frequency sweep using a 2.0 second Rabi interrogation pulse. The atomic line is observed in a single sweep with no averaging. The 2-second interrogation is nearly optimum when operating with a quartz-based LO and determines the observed atomic line Q. With the observed SNR in Figure 8, the SNR*Q inferred stability is $1.5x10^{-13}/\tau^{1/2}$ where τ is the averaging interval. When the USO is locked to the 40.5 GHz ion transition, the Allan Deviation shown in Figure 9 is obtained. The LO limited short term stability is similar to that obtained in prior ground implementations **[3]**. For comparison, the GNSS clock requirement is also shown (the "drift removed" specification accommodates current Rb clocks which can have a sizable long term linear drift). As represented earlier in Figure 3, quadrupole based ion clocks have already demonstrated long term instabilities at the 10^{-16}/day level and multi-pole ion clocks at the 10^{-17}/day level **[7]**. With these stability levels, mercury ion clocks are capable of providing autonomous timekeeping and would enable GNSS and deep space navigation applications to operate with much less frequent updates.

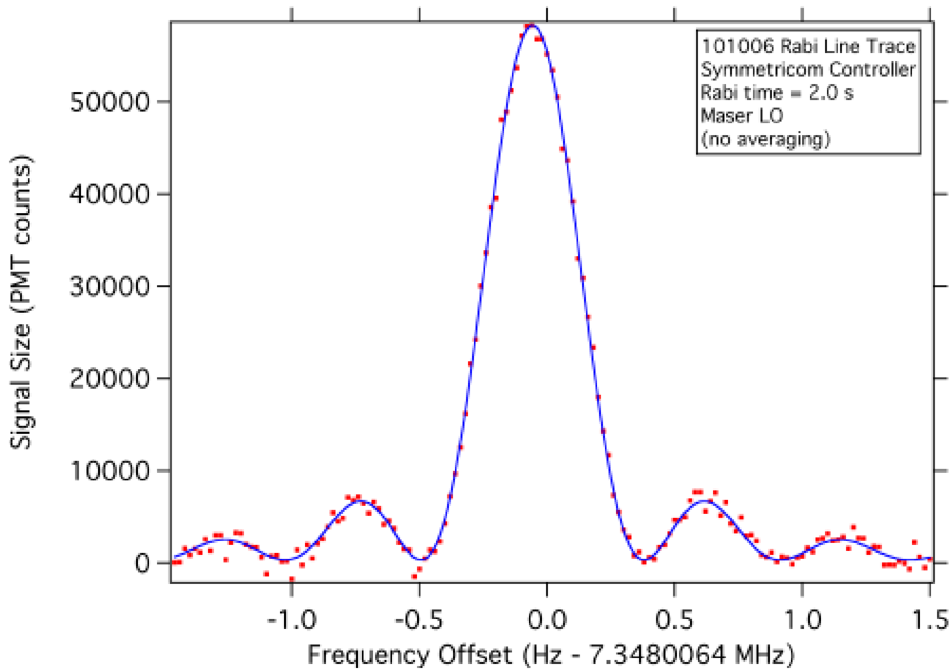

Figure 8. Measured fluorescence response of the 40.5 GHz hyperfine transition measured in the MAFS breadboard. This signal is used to servo a quartz USO with a SNR*O of $1.5x10^{-13}/\tau^{1/2}$.

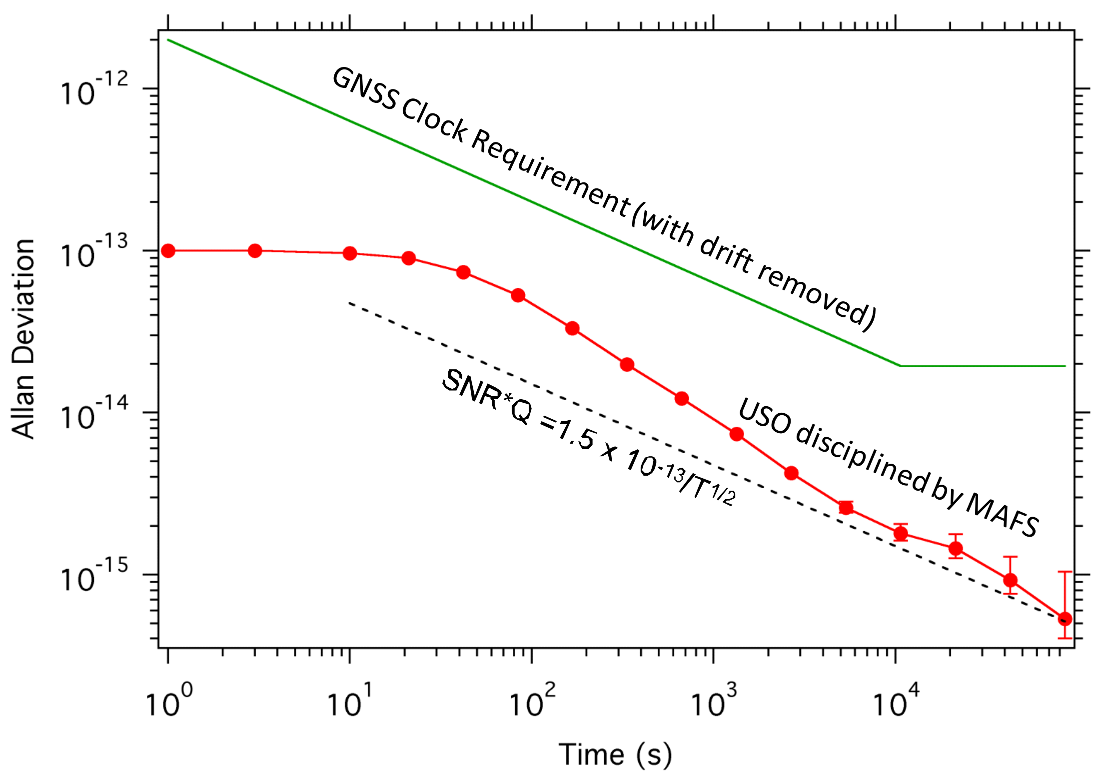

Figure 9. Short and intermediate Allan Deviation achieved in ~40W MAFS breadboard disciplining a quartz Local Oscillator.

OTHER MERCURY ION CLOCK DEVELOPMENTS AT JPL

In addition to space based GNSS application, JPL is actively developing mercury ion clocks for ultra-stable ground based timekeeping and deep space navigation application. The ultra-stable timekeeping reference standards do not need SWaP reductions or space hardening, although the trade knowledge of performance and operability strongly benefits space clock development and design trades. Figure 10 shows low power, high stability electronic assemblies recently developed for state of the art timekeeping operation with a compensated multi-pole ion trap. Small ion clock technology for potential application in deep space has also been under development for some time, with even more stringent SWaP requirements than for GNSS. Figure 11 shows a hardened ion trap/vacuum tube assembly recently assembled at JPL. Both of these developments will enhance progress towards a future MAFS Engineering Model for GNSS.

Figure 10. Ion clock assemblies engineered for low power and validation prior to integrated design.

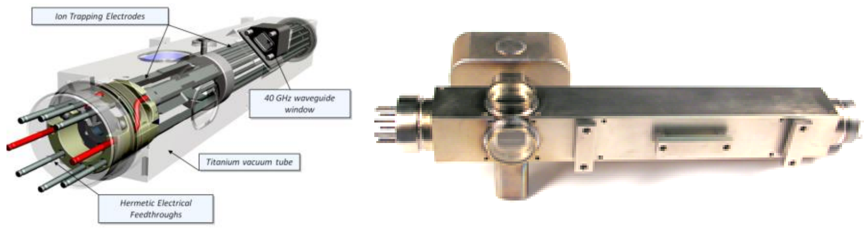

Figure 11. Ion trap/ vacuum tube assembly engineered following space vacuum tube design principles and bake-able to 450 C.

The ability of state of the art timekeeping in a small, low power instrument has recently resulted in mercury ion clock technology being selected for a demonstration mission under a new NASA technology program. A NASA goal is to significantly improve future deep space navigation capability and a stable onboard atomic clock would enable one-way navigation and other tracking, science, and autonomy benefits. A new NASA effort, dubbed Deep Space Atomic Clock (DSAC), is beginning at JPL with a goal of demonstrating 1 ns timing uncertainty at a 10 day averaging interval in flight. A mercury ion clock for deep space application needs to be small and consume very little power. State of the art long term stability for ion clock ground reference application is expected to drift at the 10^{-17}/day level or less providing time uncertainty below 100 ps at a 10 day averaging interval. GNSS clock application would require a SWaP somewhere between the DSAC clock and state of the art ground reference clock with timekeeping performance expected between the two implementations as shown in Figure 12. All three mercury ion clock implementations: 1) Deep Space Navigation, 2) GNSS based Navigation, or 3) ultra-stable ground references, are expected to provide new timekeeping capabilities.

SUMMARY

The first end-to-end, low power mercury ion clock demonstration has been made establishing the foundation for GNSS and other space application of mercury ion clocks. The demonstration was made with a getter pumped quadrupole ion trap assembly while waiting completion of engineered multi-pole trap assemblies under development in two current NASA programs; one for deep space application and one for high performance ultra-stable ground reference application. The MAFS breadboard demonstration achieved:

- Closed loop clock operation with a high quality USO disciplined to the 40.5 GHz mercury ion "clock" transition demonstrating short term frequency stability an order of magnitude better than the GPS requirement.

- Clock demonstration with an ion trap assembly evacuated with only a sealed getter pump

- Low power DC clock electronics (total ~40W).

- FPGA based digital controller developed on a simple chip set with a qualification path within the GPS parts program.

- Demonstration of a method to automatically capture and discipline the USO without a priori knowledge of its output frequency or the need for human intervention.

The key components and system demonstration are now established to advance mercury ion space clock development towards an integrated Engineering Model.

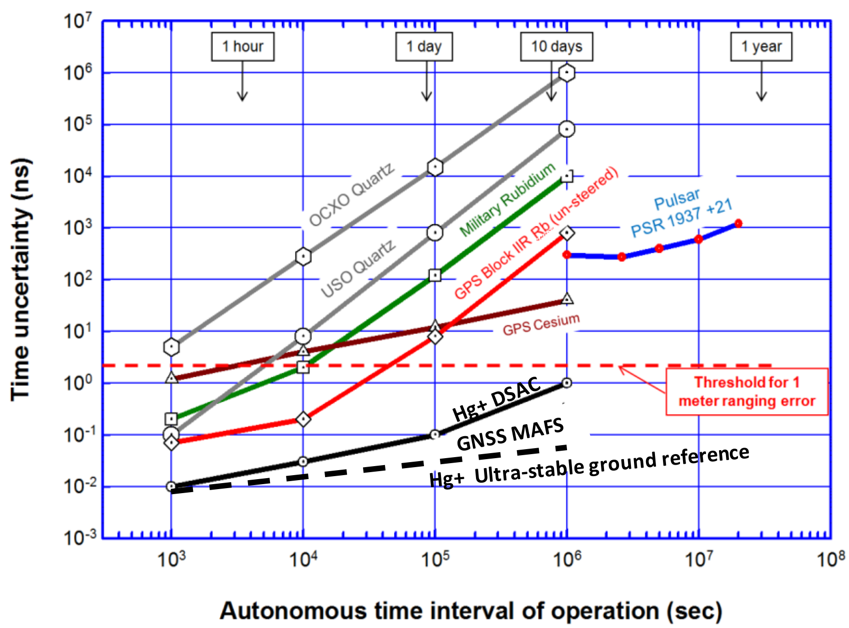

Figure 12. Time uncertainty over time for three mercury ion clock applications compared to other current space clocks.

ACKNOWLEDGEMENTS

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