MERCURY TRAPPED ION FREQUENCY STANDARD FOR SPACE APPLICATIONS

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We report on the development of a small, low mass and power, and high stability mercury trapped ion frequency standard for spaceflight. The design performance goal is fractional frequency stability reaching into the 10^{-16} range with technologies that allow for 10 years of continuous operational life. Key system elements include using a nitrogen buffer gas for long vacuum pump life and a multi-pole ion trap to minimize sensitivity to the second order Doppler shift.

1. Introduction

Atomic frequency standards capable of reliable, long term operation in space with high stability performance are needed for satellite based timekeeping and autonomous navigation applications. The use of state of the art technologies are constrained by the need for reliability, low power, mass, and volume. Flight frequency standards must also typically withstand larger environmental perturbations (e.g. thermal, magnetic, radiation, or acceleration) than experienced by high performance earthbound standards often operated in environmentally controlled metrology laboratories.

Practical high stability mercury Linear Ion Trap Standards (LITS) were developed with the goal of continuous, high stability operation for ground based applications such as the NASA Deep Space Network [1] and the USNO Timescale. The original LITS were based on a four trap electrode configuration which generates a two dimensional quadrupole potential for radial ion confinement and a dc electric field for axial confinement [2] These microwave frequency standards use the 40.5 GHz ground state hyperfine transition of ^{199}Hg+ with atomic state selection by optical pumping with 194 nm light generated from a ^{202}Hg+ discharge lamp. Ions are confined and held near room temperature with the aid of approximately 10^{-5} Torr of helium buffer gas. Since buffer gas, rf lamp based ^{199}Hg+ ion standards contain no lasers, cryogenics, or cavities they provide a significant advantage for demanding operational environments where continuous operation and high frequency stability is required.

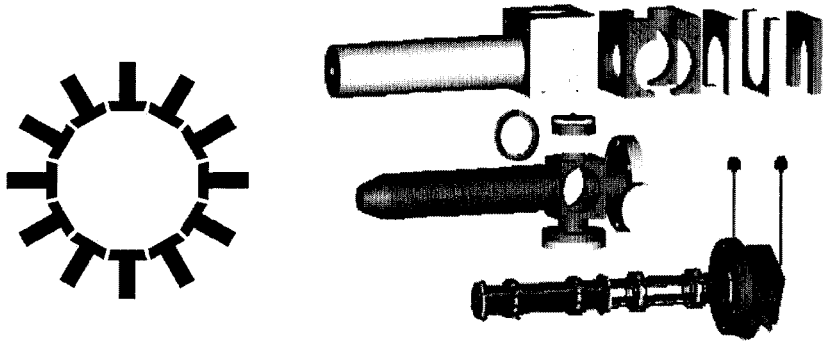

Figure 1: Space LITS Trap electrode cross section and trap, vacuum, and magnetic shield assemblies.

2. Small, Low Power, Long Operational Life Space LITS

Practical issues of power, mass, long operational life, and the space environment drive the design and technology selection for the spaceflight LITS standard. The present development program has a design goal of fitting in the existing footprint of Global Positioning System clocks with a mass and power less than 18 kg and 40 Watts respectively. The performance goal of the initial breadboard standard is to preserve the best ground based LITS performance achievable with a quartz local oscillator [1].

For brevity we only report a few key developments here that enable the flight LITS standard. They include use of a multi-pole ion trap configuration [3] and an alternative buffer gas for long vacuum pump life[4]. Other recent developments not reported include low power vacuum based lamps for optical pumping, a microgravity mercury source, miniaturization and power reduction of electronic circuits, and the development of a flight digital signal processor and FPGA system for clock operation and control. Figure 1 shows a few elements of the breadboard design including the cross section of a 12 pole ion trap and the mechanical trap, vacuum housing, and magnetic shield assemblies.

3. Multi-Pole Ion Trap: Low Thermal Sensitivity & Long Term Drift

Mulitpole ion trap geometries significantly reduce *all* ion number dependent effects resulting through the second order Doppler shift. In the current architecture ions are loaded in the original "open" quadrupole linear trap which provides needed optical

access for state preparation and detection. Approximately 10^7 ions are then moved into a "closed" multi-pole trap for microwave interrogation. Recent measurements with a 12 pole trap show reduction of the second order Doppler shift due to the confining rf fields by at least a factor of 20 [5].

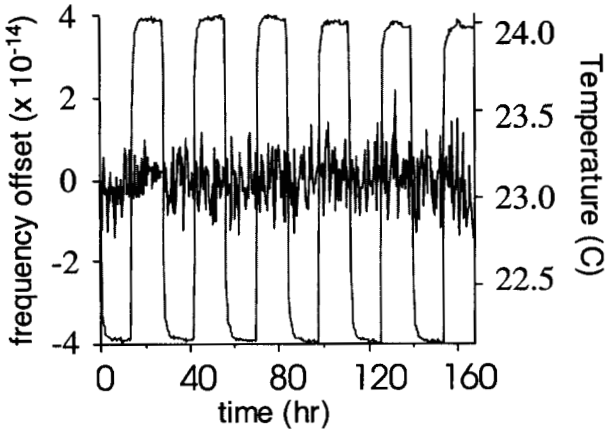

Figure 2. 40.5 GHz transition frequency residuals measured in a 12 pole trap when the external environment is changed by 2 °C.

The insensitivity to changes in ion number is also illustrated by a reduced sensitivity to ambient temperature changes. Figure 2 shows frequency residuals of the microwave clock transition measured in a 12 rod trap when the external temperature of the entire frequency standard is cycled 2 °C. Typical thermal sensitivity measured in a quadrupole LITS is 1×10^{-14} / °C [1] which traces to Hg Pressure changes and a consequent change in the loaded ion number. In measurements taken in a 12 pole trap (figure 2) the ion number dependent effects are nearly eliminated and the thermal sensitivity is reduced to $5(2) \times 10^{-16}$ / °C . For these measurements no portion of the frequency standard was thermally regulated (except the miniature Hg heater source itself). This low sensitivity implies high stability is achievable with only coarse thermal regulation of the flight standard, a major saving of electrical power.

4. Buffer Gas: Helium and Nitrogen Pressure Shifts in ^{199}Hg+

Traditionally 10^{-5} Torr of helium is used to increase ion loading efficiency and hold the ions in equilibrium with the vacuum system near room temperature [6]. Helium

is typically introduced through a high power heated quartz leak. Figure 3a shows the measured collision shift of the 40,507,347.9968x Hz clock transition in ^{199}Hg+ (F=0,m=0 to F=1,m=0) as a function of changes in the helium pressure. The measurements in figure 3 were taken using mechanical pumps with the buffer gas pressure measured with a Granville Phillips 360 series ion gauge and controller. We have performed no additional calibration of the gauge or controller beyond the factory calibration. When correcting for the ion gauge sensitivity factor of 5.56 the fractional frequency shift sensitivity of the 40.5 GHz clock transition with helium is determined to be

$$(df/dP_{He})/f = +1.7 \times 10^{-8}/\text{Torr} = +1.2 \times 10^{-10}/\text{Pa}.$$

Unfortunately helium compromises the operational life of ion pumps. For applications where pump longevity and high stability is required nitrogen has been studied as an alternative buffer gas [4]. Figure 2b shows the measured collision shift as a function of nitrogen pressure giving a clock transition sensitivity of

$$(df/dP_{N2})/f = -1.2 \times 10^{-6}/\text{Torr} = -8.7 \times 10^{-9}/\text{Pa}.$$

The ion gauge sensitivity factor for nitrogen is 1.0.

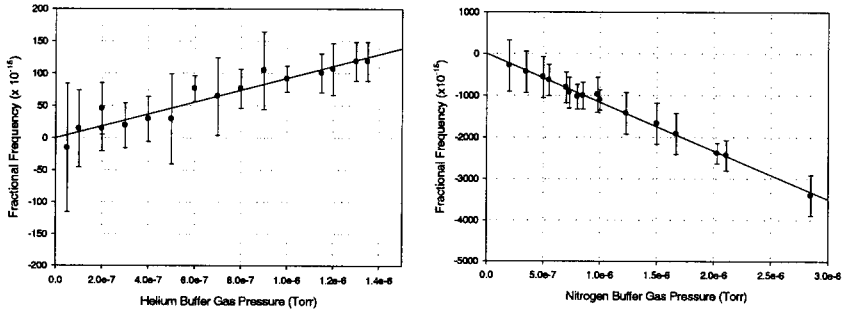

Figure 3. a) Collision shift of clock transition as a function of helium buffer gas, b) nitrogen buffer gas.

Unlike helium, nitrogen must be introduced through a mechanical precision valve or pinched capillary leak. These small orifice leaks require no power although the leak rate is a function of temperature and the gas must be free of contamination, especially condensable gases. With nitrogen a sufficient number of ^{199}Hg+ ions are loaded with a pressure of only 4 x 10^{-7} Torr, a pressure at which a small ion pump can easily operate for 10 years. Unfortunately the mercury frequency shift is about

70 times more sensitive to pressure variations than with helium (and opposite in direction).

4.1. Vacuum Pumps: Lifetime and Stability Implications

The much larger nitrogen pressure shift places a constraint on the required pressure stability. With no buffer gas stabilization the stability of the vacuum pumping speed together with the sensitivity of the collision shift determine the limit to long term stability of the frequency standard. (Active regulation requires a high precision pressure sensor adding complexity and need for power).

To examine this potential limit we scaled a capillary leak rate to give an equilibrium background pressure of approximately 4 x 10^{-7} Torr when pumped with a small commercial 2 l/s ion pump. Nitrogen pressure stability was monitored and the open loop drift observed over the first 60 days of vacuum system operation would correspond to an acceptable clock drift of 5 x 10^{-16}/ day. The drift continued to slow over time and the last 60 days of 6 months of data is shown in figure 4. This aging rate would correspond to a drift in the clock of 6 x 10^{-17}/day.

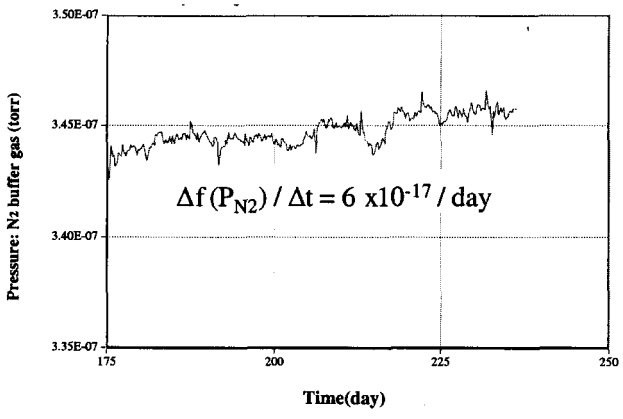

Figure 5. Unregulated nitrogen pressure stability when introduced through a pinched capillary leak into a 2 l/s ion pump system. The average drift would correspond to an average fractional frequency drift of 6 x 10^{-17} /day.

5. Summary

Small mercury trapped ion standards are poised to impact a number of flight timekeeping, autonomous navigation, and science applications requiring high performance and continuous reliable operation. A small, mechanically rugged multi-pole trap system allows the standard to be highly immune to all systematic effects coupled through changes in ion number via the second order Doppler shift. Small low power, and long life vacuum system operation is enabled using a nitrogen buffer gas with a small ion pump.

References

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