MERCURY TRAPPED-ION FREQUENCY STANDARD FOR THE GLOBAL POSITIONING SYSTEM

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Abstract

We report on progress towards the development of a small, low-mass and -power, high-stability mercury trapped-ion frequency standard for the Global Positioning System. The design performance goal is a frequency stability reaching into the 10^{-16} range using technologies that allow for more than 10 years of continuous operational life. Key features include using a multi-pole ion trap to minimize sensitivity to ion-number-dependent effects and a nitrogen buffer gas for long vacuum pump life. The development program is structured in three phases with the goal of gaining early flight experience and keeping development costs in check.

INTRODUCTION

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

Practical, ground-based, high-stability mercury Linear Ion Trap Standards (LITS) have been previously developed for continuous, high-stability operation for applications in the NASA Deep Space Network [1] and the USNO Timescale. These frequency standards use the 40.5 GHz ground state hyperfine transition of $^{199}Hg+$ with atomic state selection accomplished by optical pumping with 194 nm light generated from a $^{202}Hg+$ discharge lamp. The original four-electrode linear trap configuration generates a two-dimensional quadrupole potential for radial ion confinement and a dc electric field for axial confinement [2]. Up to 10^7 mercury ions are confined 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 are required.

LITS FLIGHT DEVELOPMENT PROGRAM

In contrast to the ground-based LITS, the design of a space flight standard is driven by issues of mass, power, operational life, and the space environment. The process of developing a new flight technology has historically been lengthy and often prohibitively expensive. With the goals of gaining early flight experience and keeping development costs in check, the Trapped-Ion Standard Flight Development Program (a.k.a. GPS-LITS) is structured into three development phases: 1) the breadboard demonstration, 2) the engineering model, and 3) the flight demonstration unit.

The primary goal of the *breadboard* development phase is to address flight requirements and demonstrate features that necessarily differ from ground-based LITS standards. The breadboard is developed as a laboratory standard, but with early involvement of experienced flight engineers to preclude design elements not amenable to future flight qualification. The breadboard demonstration is to operate as a complete standard to validate design selection and tradeoffs. The initial performance goal is to preserve the best ground-based LITS performance achievable with a quartz local oscillator [1], approximately 10-100 times more stable than present requirements for GPS clocks.

The GPS-LITS breadboard design goal is to fit the trap, vacuum, and optics assembly in the footprint of existing Global Positioning System clocks with a total breadboard mass and power less than 23 kg (50 lbs) and 80 watts respectively. This higher mass and power allows the breadboard to retain flexibility and diagnostic features for evaluation purposes. The breadboard trap, vacuum, and shield assemblies (a.k.a. the "Physics Unit") are mechanically engineered and will be shaken and thermally tested. Consumables are scaled for long-life operation of greater than 10 years. The electronic components are a first cut at simplification, size, and power reduction, and prototype circuits will be modularly packaged. Integrated flight electronics will take place in the engineering model phase when specific mission requirements are firm.

For development efforts to proceed independently, initial testing of breadboard components will be performed using mature ground-based LITS standards. The small, mechanically engineered trap electrode, vacuum, and magnetic shield assembly will be initially tested using proven ground-based electronics systems and similarly prototype electronic circuits and miniature controller initially tested using a ground-based LITS physics unit. Once complete breadboard integration and demonstration is complete and flight requirements frozen, the program moves into the engineering model phase.

In the *engineering model* phase, all instrument features and topology are finalized. Present plans call for the total mass and power to be reduced to approximately 18 kg (40 lbs) and 40 watts respectively. The engineering model will be a complete laboratory-based standard, with form, fit, and function of the flight demonstration unit except that it will be fabricated with cost-effective parts that are traceable to a "flight-qualifiable" equivalent.

The *flight demonstration unit* will be a flyable standard designed to meet the life and performance goals of an operational standard, but without the costly qualification pedigree. Plans call for it to be ground-tested and flown as a *flight demonstration experiment*. (Note: The original goal of the GPS-LITS program was to gain initial flight experience with a "flight demonstration unit" to be flown in the auxiliary payload space of a Block IIf GPS satellite. Unfortunately, the recent IIf modernization program has eliminated this technology evaluation capability.) To achieve a manufacturable clock, the engineering model design, fabrication, and operation procedures will be documented leading to the possibility of transfer to a suitable atomic clock vendor for production.

GPS-LITS BREADBOARD DEVELOPMENTS

For brevity we report only a few key developments and general design features of the GPS-LITS breadboard standard, including recent results using a new multi-pole ion trap configuration [3] and an alternative buffer gas for long vacuum pump life [4]. Other recent developments include development of a low-power lamp for optical pumping, a micro-gravity mercury source, multiple low-power electronic circuits, and design of a small digital signal processor and FPGA system for clock operation and control.

MULTI-POLE ION TRAP: LOW SENSITIVITY TO ION NUMBER AND THERMAL FLUCTUATIONS

Multi-pole ion trap geometries significantly reduce *all* ion number-dependent effects resulting through the second-order Doppler shift. Using an extended Linear Ion Trap architecture, ions are loaded in the original "open" four-electrode 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 performed in a 12-electrode trap show reduction of the ion-number-dependent shifts due to the confining rf fields by more than a factor of 20 **[5]**. Figure 1 shows the initial 3-day stability comparison between two independent 12-pole LITS standards. While not long enough to reach the flicker floor, this preliminary measurement shows the promise of multi-pole traps for applications requiring long-term stability.

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-pole trap when the external temperature of the entire frequency standard is cycled 2 °C. In contrast, typical thermal sensitivity measured in a 4-pole LITS is around 10^{-14} / °C **[1]** resulting from Hg pressure changes and a consequent change in the loaded ion number and temperature. In measurements taken in the 12-pole trap (Figure 2), 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). This low sensitivity implies high stability is achievable with only coarse thermal regulation of the flight standard, potentially a major saving of electrical power.

BUFFER GAS: COLLISION 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 has traditionally been introduced by diffusion through a heated quartz leak. The presence of a buffer gas introduces a collision shift of the ^{199}Hg+ (F=0,m=0 to F=1,m=0) 40,507,347.9968 Hz clock transition that is a function of the total helium pressure (Figure 3a). The measurements in Figure 3 were taken 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

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

Helium compromises the operational life of ion pumps and most ground-based LITS currently operate with mechanical vacuum pumps. For applications where low-power, long-life vacuum pumps are required, nitrogen buffer gas has been studied as an alternative **[4]**. Figure 3b shows the measured collision shift as a function of nitrogen pressure, giving a clock transition sensitivity of

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

The ion gauge sensitivity factor for nitrogen is 1.0.

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 and condensable gases. With nitrogen, a sufficient number of ^{199}Hg+ ions are loaded with a pressure of only 4×10^{-7} torr, a pressure at which a small ion pump can easily operate for more than 10 years. Unfortunately, as seen in Figure 3b, the collision shift with nitrogen is about 70 times more sensitive to pressure variations than with helium (and opposite in direction).

VACUUM PUMPS: LIFETIME AND STABILITY IMPLICATIONS

The much larger nitrogen pressure shift places a constraint on the required pressure stability. With no active buffer gas pressure stabilization, the stability of the vacuum pumping speed, together with the sensitivity of the collision shift, determine the limit to long-term frequency stability. (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 4×10^{-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 corresponds to a clock drift of 5×10^{-16}/ day. The pressure drift continued to slow over time and the last 60 days of 6 months of data are shown in Figure 4. This small pressure instability would correspond to a drift in the clock frequency of 6×10^{-17}/day.

LOW-POWER, LONG-LIFE LAMP DEVELOPMENT

The ^{202}Hg rf discharge lamp is a critical element, requiring low power and long operational life. Ground-based LITS lamps are presently excited with a resonator driven near 170 MHz. The 194 nm transition used for optical pumping requires relatively high power and a bright discharge to ionize ^{202}Hg. Lamps for ground-based LITS are typically operated in a two-state mode, with input power switched between a high (bright) and low (dim) state, with typical peak input power of 15 watts. The 194 nm UV lamp output is a strong function of the steady-state temperature of the lamp, a function of the switching duty cycle, the heat sink/mounting scheme, the high and low drive power levels, and any auxiliary cooling (e.g. convective or forced air).

Several developments are needed for successful lamp operation in space. The lamp must be capable of long-life operation in a vacuum environment and be easily optimized (often a subtle process). The lamp should operate both in 1 atmosphere for easy ground testing, as well as in the vacuum environment for qualification and flight. Initial tests of a ground-based LITS lamp in a vacuum system showed that the lamp temperature quickly increased and the discharge extinguished. Successful vacuum operation has now been achieved by providing a conductive heat sink between the lamp bulb and the resonator structure. To develop requirements for a self-heated thermal design, we characterized lamp effectiveness to optically pump mercury ions as a function of resonator (i.e. lamp surface) temperature. Figure 5 shows the 40.5 GHz clock transition signal-to-noise as a function of temperature. Sufficient signal-to-noise to operate the clock at high performance is achieved with temperatures between approximately 100-200 deg. C. To reduce input power, smaller discharge bulbs have also been fabricated requiring less than 10 watts to operate in 1 atmosphere. Although the new smaller, heat-sunk design has not yet been tested in a vacuum system, the required power to maintain an operating discharge is estimated to be less than 5 watts.

GPS-LITS BREADBOARD DESIGN

Figure 6 shows a few elements of the breadboard design, including the cross-section of a mechanically rugged 12-pole ion trap and the trap electrode, vacuum housing, and magnetic shield assemblies (a.k.a. the "Physics Unit"). The trap electrode assembly is constructed from molybdenum with aluminum spacers and designed to withstand 200-400 g of static load and vibration frequencies greater than 200-500 Hz. The assembly uses flexure mounts with no connectors or screws.

Figure 7 shows a high-level block diagram of the GPS-LITS electronics, functions, and organization. The breadboard power will be derived from a 28V dc power supply emulating the spacecraft power bus followed by post regulation and generation of several dc and rf sources. The Microwave chain requires a high-quality quartz VCXO as the local oscillator, and a Direct Digital Synthesizer for tracking the atomic clock transition. A controller is required to perform the clock cycle to load, state-prepare, and move ions between trap regions. The controller also measures and determines the frequency error between the atomic reference and the quartz LO. A Digital Signal Processor (DSP) with a path to flight components has been designed with the goal of moving most functions into a modern FPGA design which can be hardened for flight. Significant progress has been made developing small, modular prototype electronics, many of which are currently being tested on a ground-based LITS.

SUMMARY

A program to develop a breadboard, engineering model, and flight demonstration unit of a mercury trapped-ion frequency standard for use on advanced GPS satellites has been described. These standards should impact a number of space flight applications for timekeeping, autonomous navigation, and science requiring both high performance and continuous reliable operation. The program is in the breadboard development phase to demonstrate features unique to space flight requirements. Small low-power and long-life vacuum system operation is made possible using a nitrogen buffer gas with a small ion pump, and low-power lamps have been demonstrated. The use of a multi-pole ion trap significantly reduces sensitivity to ion number or ambient temperature fluctuations. Stability measurements performed between two ground-based multi-pole LITS standards have already demonstrated stability well into the 10^{-16} range. A small, mechanically rugged multi-pole trap system for space flight has been designed and several low-power electronic prototypes have been developed and are currently operating in the laboratory.

ACKNOWLEDGMENTS

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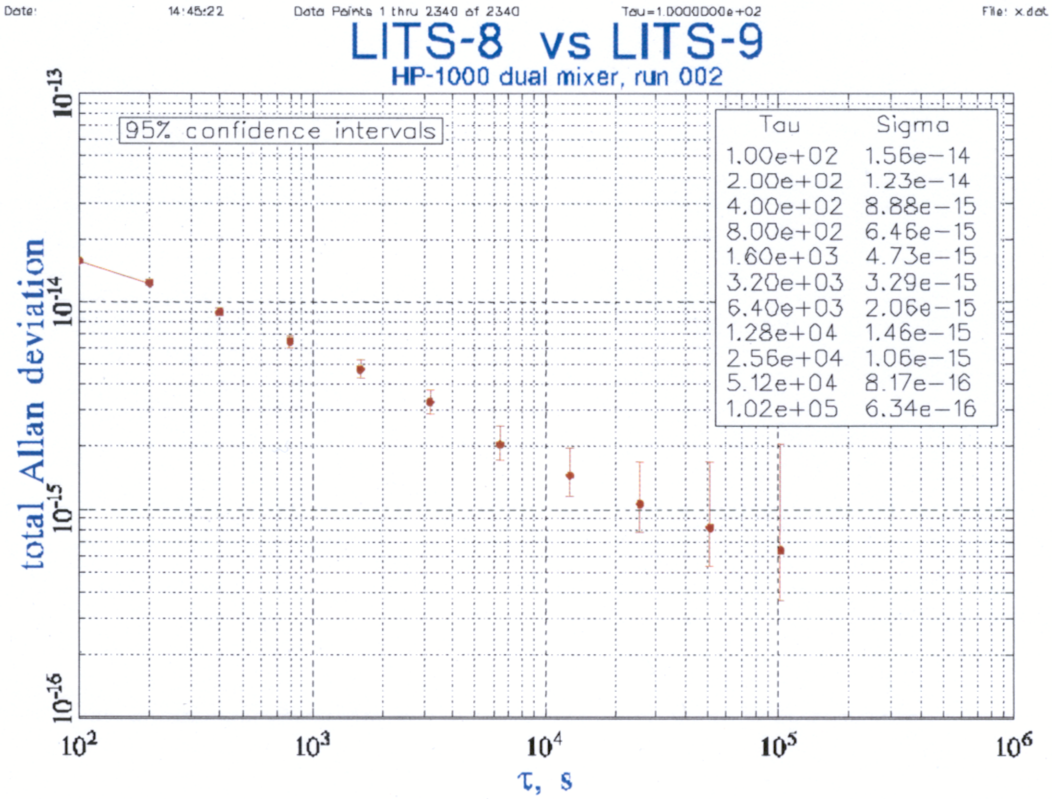

Figure 1. Allan variance showing initial 3-day comparison between two 12-pole mercury trapped-ion frequency standards.

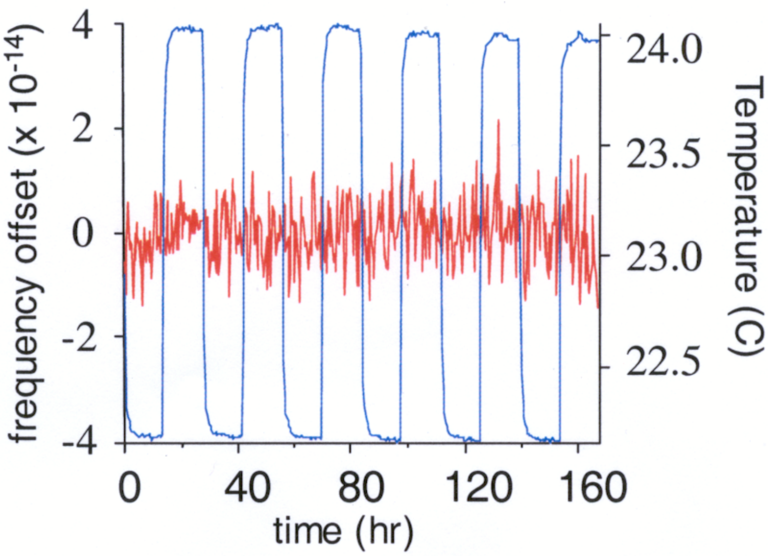

Figure 2. 40.5 GHz frequency residuals measured in a 12-pole trap when the ambient temperature is changed by 2 °C.

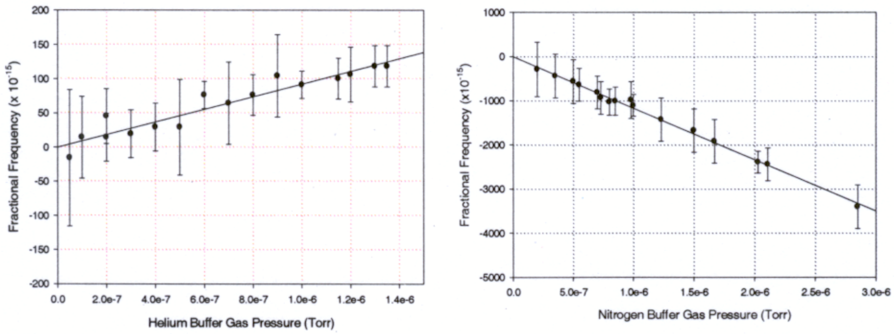

Figure 3. a) Collision shift of clock transition as a function of helium buffer gas, b) nitrogen buffer gas.

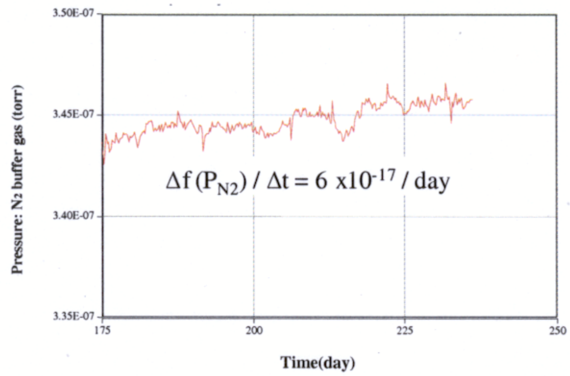

Figure 4. Unregulated nitrogen pressure stability introduced through a pinched capillary leak into a system pumped with a 2 l/s ion pump. The average pressure drift corresponds to an average fractional frequency drift of 6×10^{-17} /day.

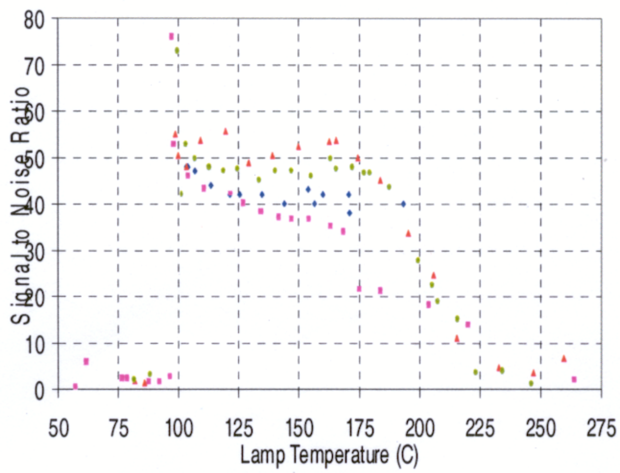

Figure 5. 40.5 GHz clock transition SNR achieved as a function of Lamp Surface Temperature.

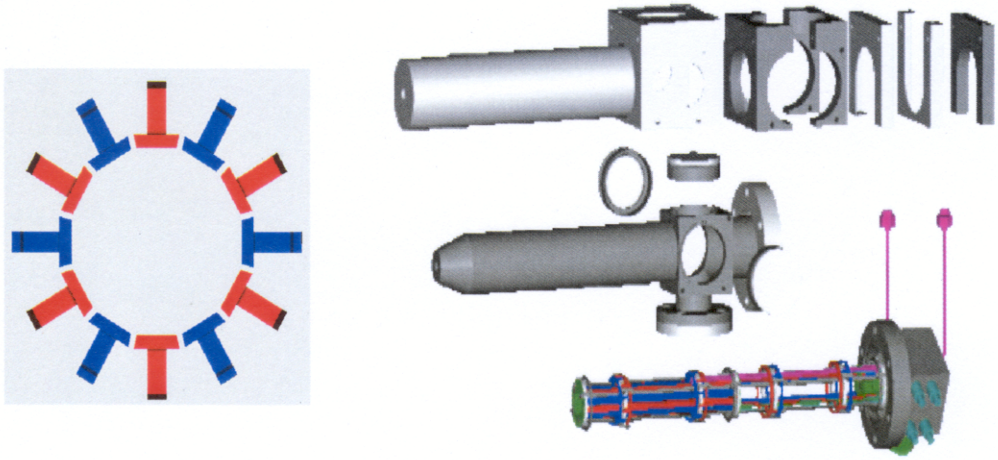

Figure 6. GPS-LITS Trap electrode cross-section and trap, vacuum, and magnetic shield assemblies.

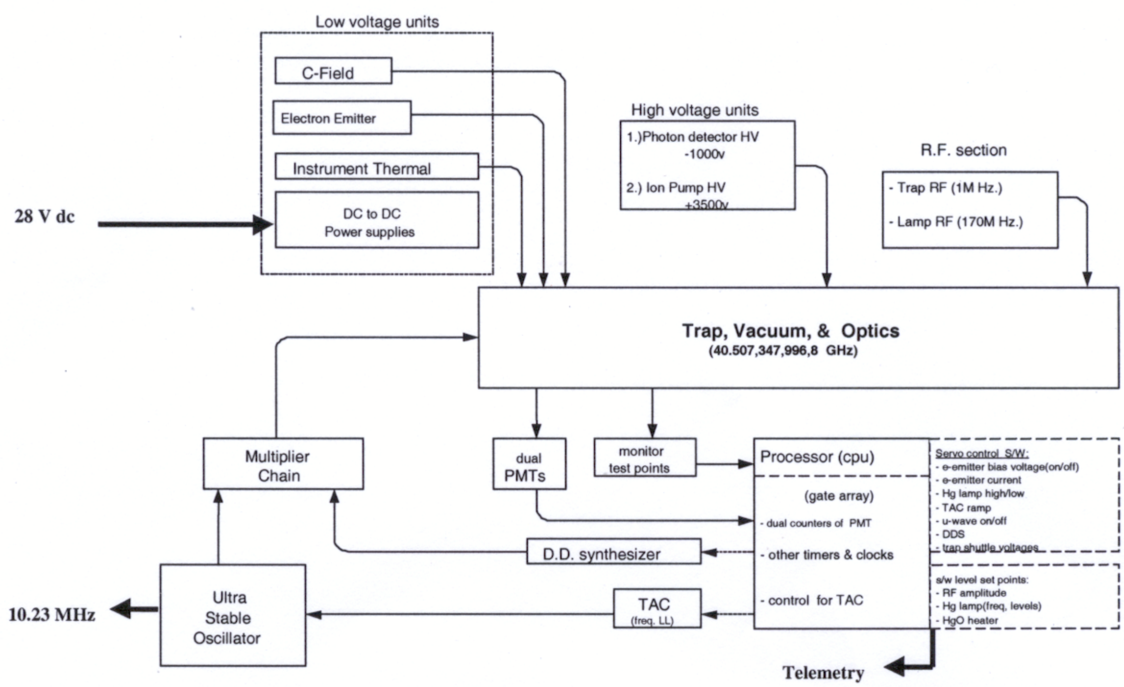

Figure 7. GPS-LITS electronic block diagram.

QUESTIONS AND ANSWERS

CHRISTOPHER EKSTROM (U.S. Naval Observatory): You showed an expected plot for flicker floor for the multi-pole trap that was connected to short-term performance of $2 \cdot 10^{-14}/\sqrt{\tau}$. Do you expect to that improvement in the flicker floor when you run the standard that hot?

ROBERT TJOELKER: Do I expect to see…?

EKSTROM: … see the 10 times improvement in the flicker floor while you are running the standard in the configuration that gives you a short-term stability of $2 \cdot 10^{-14}/\sqrt{\tau}$.

TJOELKER: Yes I do, because I think of the mid-10^{-16} range we were able to achieve in the LITS. Of course, it is a complicated issue of what folds under that flicker floor, but most of the effects in the linear trap standard are the secondary effects which couple through the secondary Doppler shift. Of course, our other big perturbations are magnetic, like any clock, which are less sensitive. Certainly, that is can be held within control to the 10^{-16} level.

Buffer gas pressure shifts are the other thing, but the helium shift is low enough on the ground that it is no problem to hold it – especially in the time frames of less than a day. You have to question running out at several weeks if you could really hold that deep of a flicker floor, because you are really living on the edge of all the subtle systematics at that point.