STABILITY MEASUREMENTS OF A JPL MULTI-POLE MERCURY TRAPPED ION FREQUENCY STANDARD AT THE USNO

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Abstract – **Two 12-pole mercury trapped ion frequency standards were recently developed and compared at JPL. In July 2002 one of these standards was installed at the United States Naval Observatory (USNO) where it has since been continuously operating. The standard is configured with a hydrogen maser as the local oscillator and is continuously compared to approximately 10 other cavity-tuned hydrogen masers, 50 cesium standards, and the USNO Master Clock UTC(USNO). Stability measurements between the trapped ion standard and several USNO formulated clock ensembles over the entire 9 month operating period to date show very stable operation with a worst case differential frequency drift between any 60 day averaging period measured to be < 2 x 10^{-16}/day.**
Keywords - **Atomic Frequency Standard, Timekeeping**

I. INTRODUCTION

Demanding ground based timekeeping and spaceflight applications require frequency standard technologies that can simultaneously provide both high stability and continuous, reliable operation. Mercury multi-pole linear ion trap standards (LITS) [1,2] offer such advantages with ongoing developments for both ultra-stable ground based timekeeping and spaceflight applications such as GPS [3] or deep space navigation [4].

Recently two JPL 12-pole LITS were developed and characterized [2,5,6,7]. In July 2002 one of these standards was delivered to the USNO where it has since been operating continuously. The LITS is currently configured with a cavity tuned hydrogen maser (NAV-19) as the local oscillator. The USNO operates approximately 10 hydrogen masers and 50 cesium beam standards as frequency and timing references [8]. With these standards the USNO formulates several ensemble averages for increased robustness and improved long term stability performance over any individual maser or cesium standard. They also formulate UTC(USNO) with measurements and corrections between their Master Clock and BIPM tying the timescale to International Atomic Time, TAI [8].

II. MULTI-POLE LITS & FREQUENCY BIASES

An ideal frequency standard for timekeeping applications would operate forever and exhibit no change in output frequency over time (i.e. long term stability). In practice, real atomic standards have frequency offsets relative to an unperturbed atomic transition of a single ion or atom at rest and in free space. These offsets can be due to multiple factors including environmental (magnetic, electric, or collision shifts) and relativistic effects. An effective primary frequency standard requires that *all* possible offsets be known at the level of reported accuracy and the ability to measure and correct for those that are larger. For secondary frequency standards, where stability and operability are the main objective, it is sufficient that the offsets be stable over time to the required level. Depending on the technology and design tradeoffs the stabilization of these offsets can be accomplished by either passive or active means.

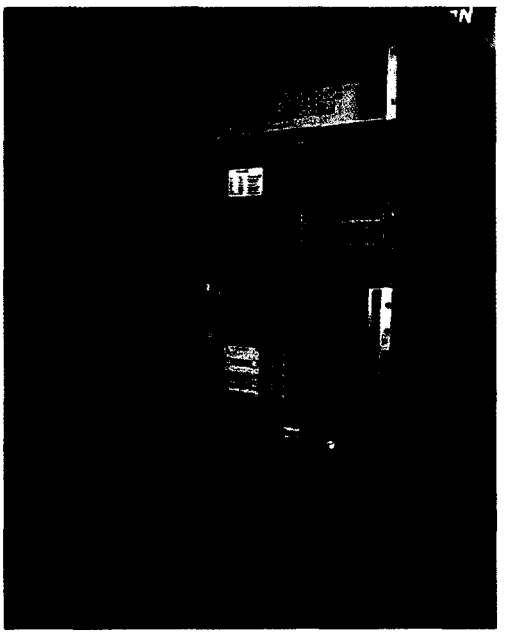

Fig. 1. JPL Trapped Ion Frequency Standard at the USNO, July 2002.

Multi-pole LITS using the approximately 40.5 GHz $^{199}Hg+$ hyperfine transition of mercury provide numerous advantages for timekeeping applications. The technology has no lasers, cavities, cryogenics, or high tolerance requirements and can give continuous high performance operation. To gain understanding on the existing capability and ultimate limitations we examine the fundamental offsets and their inherent stability.

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Frequency Offsets	LITS Frequency Offsets & Stability		
	Magnitude	Uncertainty ($x10^{-15}$)	Stability ($x10^{-15}$)
DC Magnetic (at 0.08G)	1×10^{-11}	0.1	<0.2
Shielding (24,000)			<.002 / mG
2nd Order Doppler			
Thermal (300K)	2×10^{-13}	<10	<0.2
Number Dependent	5×10^{-14}	<1	<0.1
Collision (pressure)			
Helium ($6x10^{-6}$ Torr)	10^{-13}	<10	<0.2
Mercury(10^{-9} Torr)	?	?	?
Other (<$2x10^{-9}$ Torr)	?	?	?
Blackbody	$< 10^{-16}$	< 0.1	<0.01
Gravitational Redshift	10^{-16}/m	< 0.2	

TABLE 1: CLOCK TRANSTION BIAS, MAGNITUTE, UNCERTAINTY, & STABILITY

Table 1 summarizes the known fractional frequency offsets greater than $1x10^{-16}$ in the present 12 electrode LITS system configuration. The largest of these offsets fall into three categories: magnetic, motional (Doppler), and collision (pressure) shifts. Since most of these offsets are currently unmonitored and uncorrected additional and sizable stability improvements can still be expected.

1) Magnetic Shifts: The magnetic properties of the present multi-pole base trapped ion standard have been previously measured and discussed [7]. Extensive design effort was made to insure no stray currents (e.g. thermocouple or ground loop induced) could pass through the microwave interrogation region. This region is surrounded by four nested magnetic shields with a shielding factor of 24,000. This provides a shielded sensitivity to external field variations of <2 x 10^{-18} /mG. Ambient variations at JPL are typically 1 mG over a day due to solar and the variable effects of a nearby parking lot. The peak field variations at the USNO have been higher due to a busier urban environment and activities in or near the environmental chamber housing the LITS.

An approximately 80 mG applied magnetic bias field is generated by a two-layer solenoid wrapped around the vacuum jacket. The field throughout the 1cm diameter, 20 cm long ion cloud volume is very uniform except for a small fringing field resulting from the present geometry. This is believed to be the source of a small remaining number dependent sensitivity as seen in Figure 2. This corresponds to a maximum frequency variation between an empty to full ion trap of $5x10^{-14}$ [7].

The bias field is generated from a current source derived from a very stable voltage reference and the supply is known to be stable to better than 3 ppm over many days. The sensitivity of the supply to temperature has also been characterized though the ability of the present supply to maintain the required stability over 9 months has not yet been verified. Future magnetic plans include eliminating the residual fringing field, verifying the long term stability of the current supply, and implementing an active ion measurement to monitor the average field using a sensitive Zeeman transition.

2) Thermal and Ion Number Dependent Doppler Shifts: The total Doppler shift resulting from the average ion motion can be described as the sum of shifts associated with the equilibrium ion cloud temperature and the trapping fields [1]. Due to space charge effects the later geometry dependent shift varies with the number ions in the trap. The twelve-pole trap provides a factor of 5 improvement over previous four electrode linear traps. A more dramatic benefit is that the equilibrium ion temperature is 20 times more stable as a function of ion number [2]. Further evidence of reduced "Doppler heating" is also seen in collision shift measurements at low buffer gas pressure (Fig. 3) [6].

3) Collision (pressure) Shifts: Collisions with background gas cause unwanted frequency shifts. The typical gases present in the LITS ultra-high vacuum system are helium, hydrogen, CO, CO_2, and mercury. Helium is introduced as a buffer gas through a heated quartz leak and is maintained near $6x10^{-6}$ Torr. Because of the negligible Doppler heating at low buffer gas pressures collision shift sensitivity calibration

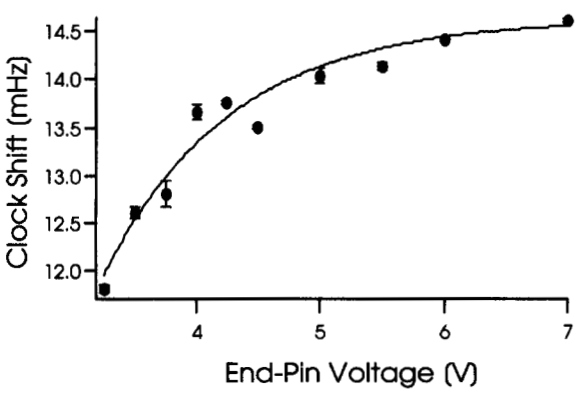

Fig. 2: Anomalous Doppler Shift showing the maximal frequency excursion possible ($5x10^{-14}$) while varying the number of ions in the trap via the end-pin electrode voltage [7].

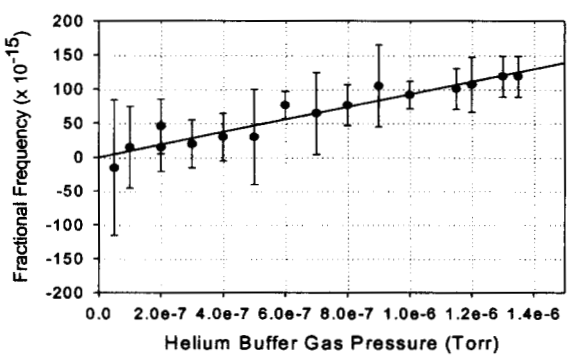

Fig. 3. Frequency Shift as a function of indicated helium pressure [6]. (note: the actual pressure is 5 times higher).

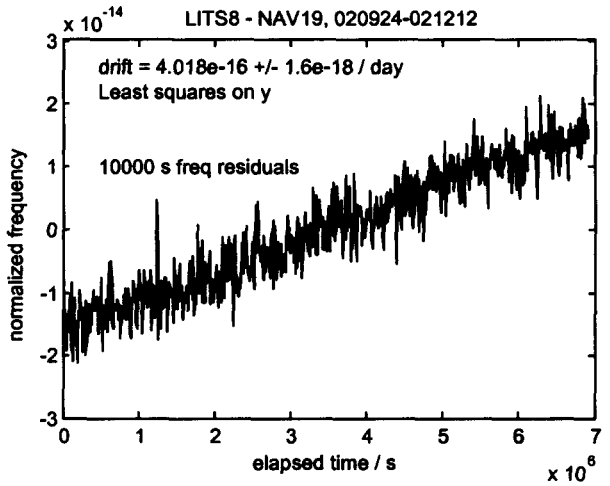

Fig. 4a: Frequency residuals between the LITS and the hydrogen maser Local Oscillator (NAV-19). The 4.0 x 10^{-16}/day drift was determined to be primarily contributed by the hydrogen maser.

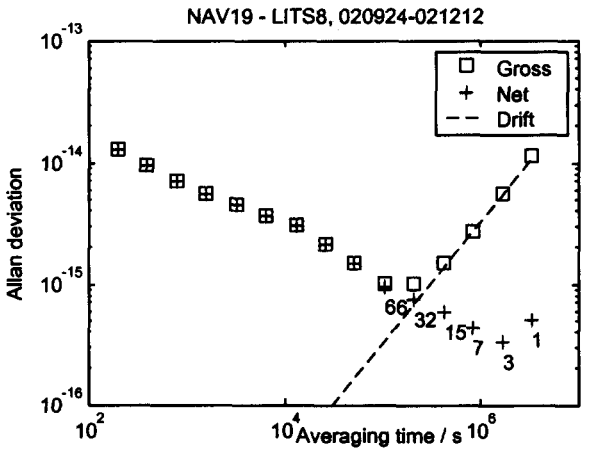

Fig. 4b: Allan deviation of the residuals shown in Fig. 4a. Also shown is the linear drift of the reference maser removed, showing stability consistent with direct LITS-LITS comparisons [4].

measurements in a multi-pole LITS is straight forward [6]. For timekeeping applications the challenge becomes knowing the precise makeup of the background gases and controlling their stability over long periods of time. The partial pressure components, magnitude, and stability depend in part on the vacuum system design and preparation, selected vacuum pumps, and the means used for measuring or controlling the partial pressures.

The multi-pole LITS at the USNO currently operates with mechanical vacuum pumps and a helium buffer gas pressure regulated to a measurement with a commercial ion gauge and controller. The ion gauge senses the total system pressure, primarily helium, which has its limitations. For example, the stability of the ion gauge filament, electrometer, and the partial gas pressures themselves may change over time. The long term vacuum stability is also presently compromised by use of an oil free, diaphragm forepump backing a turbo-molecular pump. Since this pump combination provides only marginal pump speed for light gasses we anticipate partial pressure variations of hydrogen over time (or as a function of temperature) may result.

The collision shift of Helium is shown in Figure 3 though measurements have not been performed with HgO, CO_2, CO, and H_2. Nitrogen has also been measured and studied as a possible buffer gas for long life space-flight operation [6]. Ongoing long term vacuum studies with a small ion pump and introducing N_2 buffer gas through a capillary leak have shown excellent unregulated stability corresponding to a frequency stability limit of $<10^{-16}$/day. This is achieved even though the collision shift with of N_2 is 80 times larger than with helium. Capillary leaks operating in a good thermal environment may be more stable in the long term than the active servo to an ion gauge. This modification is being considered for the timekeeping application at the USNO.

III. RESULTS AT JPL

A. LITS – LITS Comparisons :

Long term stability comparisons between two quadrupole LITS have been previously made where a performance tradeoff exists when configuring the standard for good short term stability performance [9]. This requires operating with as large of ion cloud as possible resulting in further ion heating and Doppler pulling. The multi-pole trap greatly reduces this tradeoff as the ion temperature remains nearly constant for all sizes of the ion cloud. Direct stability comparisons between two multi-pole LITS for durations up to one week have been previously reported [5].

B. System Thermal Sensitivity

The thermal sensitivity of the unpackaged multi-pole standard (i.e. no instrument thermal control) is typically measured to be around 4×10^{-15}/deg C. The source of this is under investigation though a leading candidate is the possibility of variation, and consequential collision shift, of light gases such as hydrogen. At JPL the LITS typically operates in a controlled thermal environment stable to 0.05 degrees C. For delivery to the USNO the standard was packaged into an enclosure thermally controlled to better than 0.1 degree stability. The stability limitation of this remaining thermal sensitivity and level of control is under study.

C. Relocation of the LITS and Frequency Reproducibility

In July 2002 a multi-pole LITS standard shown in Figure 1 was moved from the JPL Frequency Standards Laboratory in Pasadena, California to a USNO clock vault in Washington D.C.. The LITS was turned off, crated, moved via truck to the airport, transferred between two planes, and finally trucked and started at the USNO. The entire process of shutdown to startup took approximately 24 hours. Before shutdown the frequency offset of the standard was measured at JPL with respect to UTC(NIST). Once installed at the USNO it was measured against UTC(USNO). Taking into account the elevation change of nearly 400 meters the LITS frequency was reproducible to $<2\times10^{-14}$ even with shipping and power cycling. This reproducibility is consistent with the magnitude and offset stability outlined in table 1.

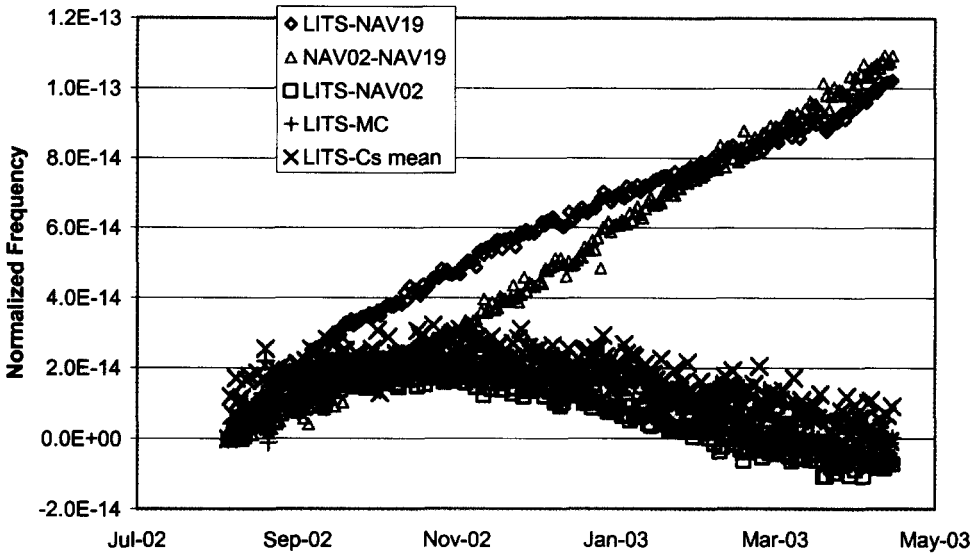

Fig. 5: Frequency residuals of the LITS with respect to two hydrogen masers (NAV-19 and NAV-2), the USNO Master Clock, and the mean of the USNO Cesium Standards. For the 3 month span from September –December 2002 the relative drift between the LITS and the USNO ensembles was less than 5×10^{-17}.

IV. MEASUREMENT CONFIGURATION AT THE USNO

The USNO, located in central Washington D.C. is responsible for generating and maintaining the U.S. DoD Master Clock, UTC(USNO). The physical realization of UTC(USNO) is a hydrogen maser steered to an internally generated timescale that is steered to UTC as reported by BIPM. The USNO maintains dozens of frequency standards which are distributed and compared across several buildings [8]. The routinely available standards are commercial cavity tuned H-masers [10] and cesium standards [11]. The USNO formulates many different ensemble averages which could include noise or possible instabilities from the interconnections, the comparison systems, or the ensemble algorithms themselves.

The LITS was installed in a thermal chamber shared with two cavity tuned hydrogen masers. One of the masers, referred to as NAV-19, served as the LITS Local Oscillator. The multi-pole LITS standards was configured to operate with a 6 second microwave interrogation time and a short term performance of $1.7 \times 10^{-13}/\text{tau}^{1/2}$. A complete interrogation cycle takes approximately 12 seconds. Once each cycle the frequency error between the LO maser (NAV-19) and the LITS, along with other telemetry data, are recorded by a monitor computer accessible by the internet.

V. LONG TERM STABILITY COMPARISONS

The LITS standard began operating at the USNO on July 20, 2002 and has been continuously operating since. The initial measurement configuration allowed for direct access to the error signal between the LITS and the maser NAV-19. This maser is referenced to all other USNO standards so to compare the LITS stability against other standards or ensembles required differencing out NAV-19.

Initial long-term measurements (September-December 2002) taken between the LITS and NAV-19 are shown in Figures 4a and 4b. An approximately 4×10^{-16}/day linear differential frequency drift was measured that remained constant over months. A USNO comparison of NAV-19 against an independent average of approximately 10 detrended hydrogen masers (referred to by the USNO as the "maser mean") indicated that the 4×10^{-16}/day relative drift observed in Figure 4a was primarily due to NAV-19. When differencing out NAV-19 the LITS compared to the "maser mean" yielded a differential drift of $<5 \times 10^{-17}$/day over the 2.5 month period.

The frequency residuals of the LITS over the entire 9 month period of operation to date is shown in Figure 5 against a number of USNO references. Interpreting comparisons to ensembles is challenging since correlated and uncorrelated noise from the measurement, environment, and connections between distant standards also contribute to the measured long-term instabilities. Figure 5 shows the LITS compared to 1) the USNO Master Clock 2) a "mean" of approximately 50 cesium beam frequency standards and 3) the LO maser NAV-19. Also shown is a measurement with respect to the individual maser NAV-2. This was identified as the most stationary maser at the USNO with respect to the BIPM during this measurement interval. NAV-2, which also resides in the same building as the LITS, provides a better short-term reference and reduced link noise than any of the

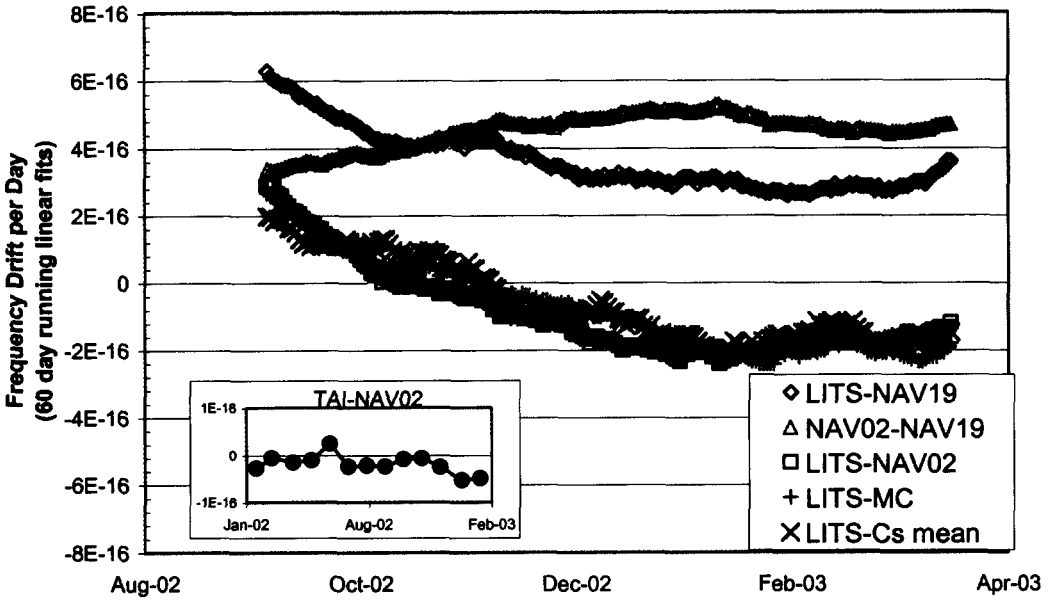

Fig. 6: The relative frequency drift per day made by taking a 60 day running linear fits to the data in Figure 5. The cesium mean and the USNO Master Clock (MC) are somewhat correlated . The average drift rate of the Local Oscillator (NAV-19) of approximately $4x10^{-16}$/day is evident.

measurements against the more involved ensembles. For reference a comparison between the two masers NAV-19 and NAV-2 is also shown.

As there is no perfect long-term reference, measurements against ensembles can be misinterpreted and none of the ensembles shown are entirely uncorrelated. The generation of TAI involves many primary standards and global satellite time transfer which are not noise free systems. Nevertheless UTC is pinned at some level by primary standard calibrations with consistent agreement near the $1x10^{-15}$ level. As such this gives confidence that the $2x10^{-14}$ frequency variation of the LITS as shown in Figure 5 over a 9 month period is real.

Figure 6 presents a different view of the data in Figure 5. Here we show the relative frequency drift between the various USNO references and the LITS by using a running 60 day averaging window. It is noteworthy that the peak to peak variations of $1x10^{-16}$/day exist between different ensemble references suggesting that it is currently not meaningful to characterize the drift uncertainty of any measurement at less than $1x10^{-16}$ per day.

VI. DISCUSSION AND FUTURE DIRECTIONS

The LITS has been operating at the USNO in "open loop" operation with the three largest offsets outlined in Table 1 not monitored or corrected. The measurements show a worst case relative drift of $2x10^{-16}$/day from a cold startup and a 2.5 month period where the differential drift between the LITS and the most stable USNO ensemble was measured to be 5(10) x 10^{-17}/day. Currently we conclude that over the 9 months of operation that the LITS frequency has moved by up to $2x10^{-14}$. Similar systematic variations are also common in many primary laser cooled cesium clocks, the difference being that the offsets are calibrated and corrected for [12].

One possibility for the $2x10^{-14}$ variation over 9 months is the magnetic field, possibly either a slow degaussing of the magnetic shields, or instabilities in the current supply. The technique to measure magnetic variations [7] could be permanently implemented. The ion cloud average temperature can be measured and monitored by longitudinal microwave interrogation [13]. Pressure shifts/calibrations for He and N_2 have been previously measured though further measurements, especially with H_2, need to be performed. The effect of IG control on the helium pressure stability and on partial pressure stability with the current vacuum pump configuration need to be further studied. N_2 buffer gas systems with small ion pumps and capillary leaks have shown excellent promise for long term stability for ground or low power, long operation spaceflight applications.

Measuring these three offsets below the 10^{-14} level would allow servo or the ability to correct for the remaining long term frequency variations. Plans to further understand the residual instabilities and to begin remote GPS carrier phase comparisons between two Multi-pole LITS, one located at the USNO and the second at the Frequency Standards Test Laboratory at JPL are underway.

VII. CONCLUSION

The mercury trapped ion standard using a multi-pole trap electrode configuration is poised to have a significant impact on ground and space based timekeeping applications. The first timekeeping results obtained at the USNO are very encouraging where a LITS has been operating continuously since July 2002. This technology is independent from the traditional hydrogen masers and cesium beam standards used by the USNO to form a number of ensemble averages and means. LITS performance measured against the best ensemble averages and the master clock show the relative frequency drift to be $< 2\times10^{-16}$ /day over any 60 day averaging interval. In fact for a nearly 3 month interval the relative frequency drift between the USNO ensemble and the LITS was $<1 \times 10^{-16}$/day (our estimated noise floor). The LITS is un-steered and the data is not corrected for possible variation of the largest frequency offsets, which currently go unmonitored. The reproducibility of the standards to power down and shipping is also very encouraging.

For further improvements it will be beneficial to measure and monitor the known biases. These include the magnetic environment at the ions via Zeeman resonance, ion temperature via Doppler linewidth measurements, and improving the vacuum system scheme to reduce light gas background pressure variations.

The LITS technology with unsteered and uncorrected stability at the 10^{-16}/day level is very amenable for autonomous timekeeping and small, low power, and long life spaceflight applications.

ACKNOWLEDGMENT

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