PROSPECTS FOR ULTRA-STABLE TIMEKEEPING WITH SEALED VACUUM OPERATION IN MULTI-POLE LINEAR ION TRAP STANDARDS

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Abstract

A recent long-term comparison between the compensated multi-pole Linear Ion Trap Standard (LITS) and the laser-cooled primary standards via GPS carrier-phase time transfer showed a deviation of less than 2.7×10^{-17}/day. A subsequent evaluation of potential drift contributors in the LITS showed that the leading candidates are fluctuations in background gases and the neon buffer gas. The current vacuum system employs a "flow-through" turbo-molecular pump and a diaphragm fore-pump. Here, we consider the viability of a "sealed" vacuum system pumped by a non-evaporable getter for long-term ultra-stable clock operation. Initial tests suggest that both further stability improvement and longer mean-time-between-maintenance can be achieved using this approach.*

INTRODUCTION

A compensated multi-pole Linear Ion Trap Standard (LITS) developed at the Jet Propulsion Laboratory (JPL) has recently demonstrated extremely good long-term stability over a 9-month period **[1]**. The short-term stability of this clock has been measured at $5\times10^{-14}/\tau^{1/2}$ and all contributions to systematic stability have been measured to be less than 5×10^{-17}. An upper limit on fractional frequency drift $<2.7\times10^{-17}$/day was measured in comparison to the laser-cooled primary standards using GPS carrier-phase time transfer.

This clock is designed for continuous operation and is able to run uninterrupted for up to 2 years, limited primarily by the need to perform maintenance on the mechanical fore-pump used in conjunction with a turbo pump. This "flow-through" vacuum system is used because of the need to pump unwanted background gases in the presence of a relatively large buffer gas pressure. Whereas an ion pump would quickly become saturated with the noble buffer gas, the turbo pump provides a much longer operating life and provides a stable pumping speed. Sealed pump buffer-gas-cooled ion trap clocks using a getter/ion pump combination have operated for up to 5 years in prior timekeeping applications, but exhibited significant drift rates **[2]**. For spacecraft applications, a vacuum system loaded with a getterable buffer

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gas and pumped by only a small ion pump was operated for several years. The measured buffer gas pressure variation in an open loop system corresponds to a long-term stability limit in a mercury ion clock due to the pressure shift of 6×10^{-17}/day **[3]**.

An alternative vacuum pumping strategy uses only a getter pump, which does not pump inert gases such as the current neon buffer gas. With a fixed quantity of buffer gas, a getter pump could provide decades of operation with no interruption provided that the outgas rates of both getterable and non-getterable gases are sufficiently low. Operation of LITS technology in a small sealed vacuum system baked out to very high temperatures and pumped using only a getter pump has shown encouraging results towards achieving long operational life **[4]**. In addition to greatly extending the time between maintenance interruptions, this approach simplifies needed electronics and may possibly lead to an even more stable vacuum environment. However, at present, details of the long-term evolution of gases not pumped by the getter are poorly understood. In this paper, we present initial tests on the long-term behavior of such gases in the presence of a getter pump and discuss the viability of this approach for ultra-stable timekeeping applications.

THE COMPENSATED MULTI-POLE LITS

The multi-pole Linear Ion Trap Standard (multi-pole LITS) consists of a conventional linear quadrupole trap for ion loading and state preparation/readout and a second 12-pole trap to hold ions during the interrogation of the microwave clock transition **[5]**. The multi-pole trap significantly reduces the ion-number-dependent second-order Doppler shift. The compensated multi-pole LITS further reduces this sensitivity by using a small stable inhomogeneous magnetic field to compensate any remaining second-order Doppler shift **[6]**. This frequency standard also uses a neon buffer gas to minimize the buffer gas pressure shift and has achieved a short-term stability of $5\times10^{-14}/\tau^{1/2}$.

LONG-TERM PERFORMANCE

To demonstrate the new level of performance achieved by the compensated multi-pole LITS, this standard (known as LITS9) was compared to several UTC (k), UTC, and to the laser-cooled primary standards using GPS carrier-phase time transfer **[1]**. Fig. 1 shows the Allan deviation of fractional frequency offsets between LITS9 and UTC (NIST). The measurement is limited at the 10^{-15} level by GPS noise, but shows no significant drift over the 9-month run. Also shown in the graph is the stability of an *uncompensated* multi-pole LITS compared to the USNO Master Clock **[7]** (the short-term stability is masked by measurement noise). The improved long-term stability achieved by applying the magnetic compensation is readily apparent.

By double-differencing these data with UTC (NIST) – UTC data, we are able to obtain LITS9 – UTC. Frequency offsets for LITS9 – UTC obtained in this way are shown in Fig. 2. A straight-line fit to these data gives a relative drift rate of 3.3×10^{-17}/day. This can be viewed as an upper bound on LITS9 performance, as the comparison also includes GPS noise and steers to UTC.

A further double-difference with all laser-cooled primary frequency standards reporting accuracy evaluations (frequency offsets from TAI) over the same time period gives a relative deviation between LITS9 and those standards of 2.7×10^{-17}/day.

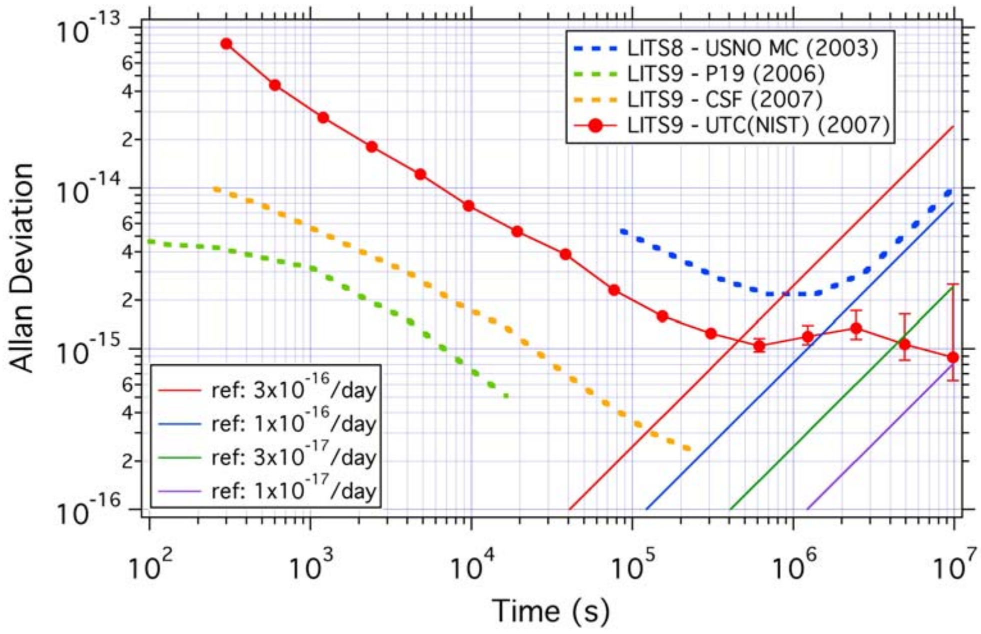

Figure 1. The Allan deviation of fractional frequency offsets between LITS9 and UTC (NIST) (red lines connecting solid circles). The dashed green line shows the short-term stability relative to a local hydrogen maser and the dashed yellow line shows the stability relative to a local laser-cooled cesium fountain clock. Both of these measurements show that GPS noise limits the GPS carrier-phase measurements over the short to medium term. The dashed blue line shows the stability of the uncompensated multi-pole LITS as compared to the USNO Master Clock.

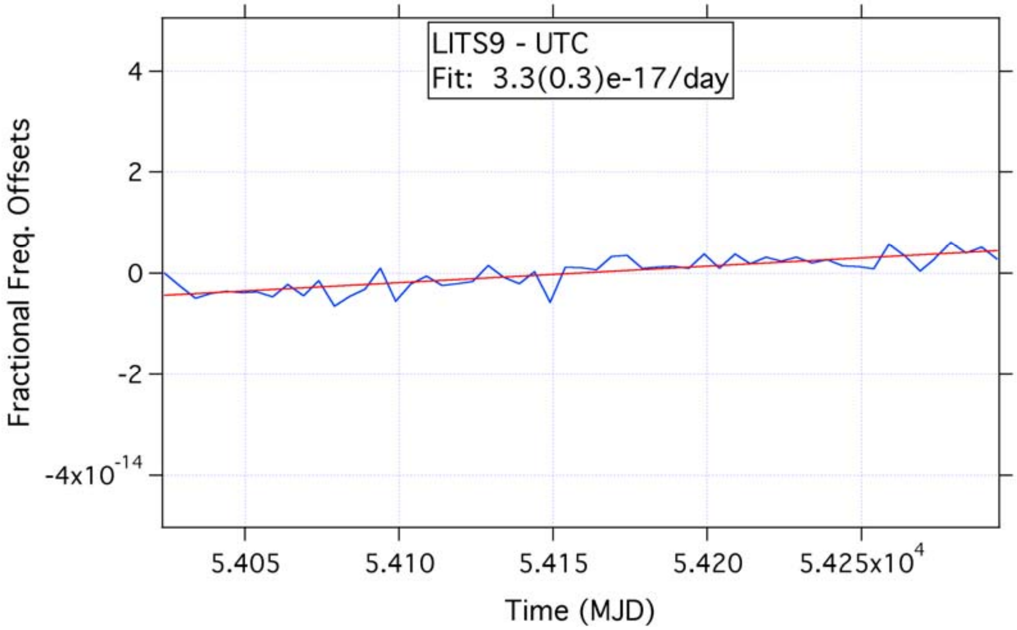

Figure 2. Fractional frequency offsets between LITS9 and UTC over 9 months.

STABILITY EVALUATION

An evaluation of all possible contributions to instability over the 9-month run was performed. For each effect, the underlying variation was either measured or estimated over the comparison duration. The results are summarized in Table 1. The largest effects are the temperature-dependent 2nd-order Doppler shift, various collision shifts, and number-dependent shifts (including both number-dependent magnetic and 2nd-order Doppler shifts). Before ion number compensation was implemented, ion-number-dependent effects were the largest contributor to long-term clock instability. Now the largest remaining effects are due to collisions with either the buffer gas or other residual background gases. Note that the largest uncertainty is in the temperature-dependent effect. This is because the ion temperature is not directly measured and must be inferred from other measurements. The estimated total clock instability agrees with the measured instability at the 2-σ level. More important, however, is the fact that the largest remaining contributors to instability are related to vacuum pressure.

SEALED VACUUM SYSTEM

The stability evaluation just described highlights the background gas pressures and their associated effects as the largest uncertainty in clock performance. Part of this is due to the fact that the current vacuum system has a “flow-through” configuration that uses a turbo-molecular pump and a diaphragm fore-pump. When allowed to reach equilibrium, such a system can be stable at the 10^{-10} torr level; however, fluctuations in some gases at this level can cause significant frequency shifts. It is also possible for light gases to “back-stream” through the mechanical pumping system, causing their associated partial pressures to vary over time, thereby leading to long-term clock drifts.

To address background gas stability, we have converted the compensated multi-pole LITS to a sealed-pump vacuum system using only a non-evaporable getter. Stable signal-to-noise has already been achieved in a small system that is designed to withstand high-vacuum bake-out temperatures (450 C) **[4]**; however, the LITS9 is only designed to withstand a bake-out temperature of 200 C. It remains to be determined what the long-term evolution of gases, particularly non-reactive noble gases, will be in such a system. While the estimated getter life can be very long (potentially decades), this still needs to be demonstrated. Currently, the LITS9 maintenance cycle is determined by the lifetime of the diaphragm fore-pump – about 18 months. It is possible that the time between activations for the getter pump could be significantly longer, thereby reducing interruptions to clock operation.

INITIAL RESULTS

To gauge the effectiveness of a getter pump in maintaining a sufficiently low pressure and to determine the rate at which ungetterable gases would accumulate, we built a test system consisting of a vacuum chamber (similar in volume to LITS9) with both an ion gauge and a residual gas analyzer (RGA) to monitor pressure evolution. The test system was baked to ~200 C for 5 days. The bake-out was performed using a turbo-molecular pump. After the bakeout was complete and the pressure reached equilibrium, the turbo pump was valved off and the pressure was allowed to evolve in the presence of the getter pump, the RGA, and an ion gauge. After a period of 6 days, the ion gauge was also turned off. See Figure 3.

The test revealed that only argon and neon showed significant pressure increases over the 30-day test period. Some partial pressures decreased when the ion gauge was turned off, indicating that the ion gauge generates these gases. Some partial pressures increased, suggesting that the ion gauge either pumped or affected the RGA readings for these gases.

Table 1. Summary of LITS-9 stability evaluation. The “Change” column shows the amount of change in the underlying cause over the 9-month run of the item listed in the “Effect” column. “Sensitivity” shows the fractional frequency sensitivity in the clock due to this underlying cause. “df/f” shows the actual fractional frequency shift in the clock due to this effect over the 9-month run. “Uncertainty” gives the error in the estimate of df/f. When only an upper bound is measured (the effect is consistent with zero within the error estimate), only the uncertainty is given. Pressure-related effects are highlighted.

Effect	*Change*	*Units*	*Sensitivity*	*Units*	*df/f (x10^{-17})*	*df /f (x10^{-17}/day)*	*Uncertainty (x10^{-17}/day)*
Temperature-dependent 2nd-order Doppler	$-4.57(1)\times10^{-7}$	torr (neon buffer gas)	$< \pm2.0\times10^{-8}$	/torr-neon	-510	-1.9	±3.4
Collision shift (neon)	$-4.57(1)\times10^{-7}$	torr	+344(68)	Hz/torr	-388	-1.4	0.1
Collision shift (CH_4)	$< 7\times10^{-11}$	torr	-1.46	MHz/torr			< ±1
Number	-0.32	dN/N	+289(31)	μHz/(dN/N)	-230	-0.8	0.2
collision shift (Hg)	$< 1.2\times10^{-10}$	torr	< ±380	kHz/torr			< ±0.41
GPSCPTT	--	--	1×10^{-15}	Fractional Frequency Accuracy			< ±0.4
C-field current source aging	$-4.6(2.9)\times10^{-5}$	mA	0.4997	Hz/mA	-57	-0.21	0.13
External field	< ±1	mG	+15.2(1.7)	μHz/mG			< ±0.1
Compensation Coil current source aging	$2.0(0.6)\times10^{-2}$	mA	-0.526	mHz/mA	-26	-0.095	0.027
collision shift (H_2)	$< 2.2\times10^{-10}$	torr	-40.5	kHz/torr			< ±0.081
Microwave power	< 0.5	dB	< ±11	μHz/dB			< ±0.05
Ambient Temperature	+0.274	C	+10.5(4.9)	μHz/C	+7.1	+0.03	0.01
Light shift	-59(20)	PMT Counts (dD)	-0.12(0.12)	μHz/(dD/D)			< ±0.0002
Total					-1220	-4.5	3.6

Fig. 4 shows an expanded view of the neon gas evolution. The initial (worst case) slope would correspond to a fractional frequency shift in the clock frequency of 3.0×10^{-19}/day. The data fit well to an exponential with a time constant of about 22 days. The exponential character is indicative of a virtual leak: as the pressure on either side of the virtual leak comes to equilibrium, the indicated pressure will stop increasing. In contrast, an external leak (at this level) would appear to increase linearly.

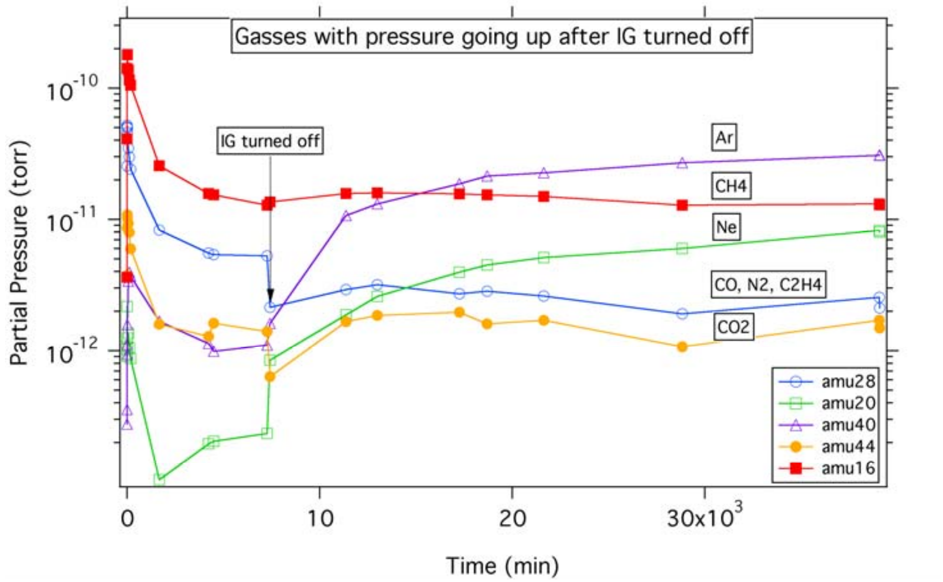

Figure 3. Pressure evolution for a test vacuum system using only a getter pump. Only partial pressures for gases whose pressure increased at some point during the test are shown.

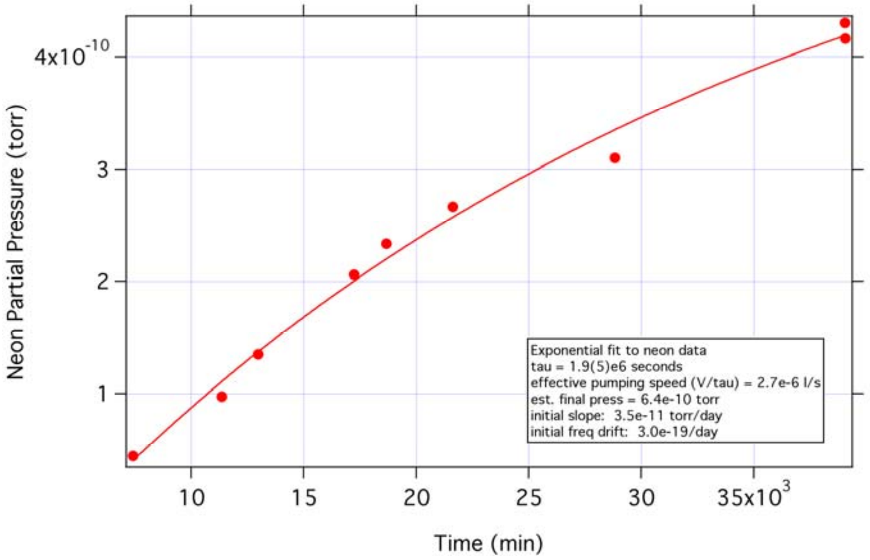

Figure 4. Detail of neon pressure evolution. The initial slope corresponds to a clock fractional frequency shift of 3.0×10^{-19}/day and fits to an exponential with a time constant of about 22 days.

A detail of the argon pressure evolution is shown in Fig. 5. The argon pressure is changing faster than the neon, but also is changing exponentially. The initial slope (worst case) corresponds to a clock shift of -5×10^{-18}/day and the exponential has a time constant of about 9 days. For both neon and argon, the clock shift after several months of settling time would be virtually nonexistent.

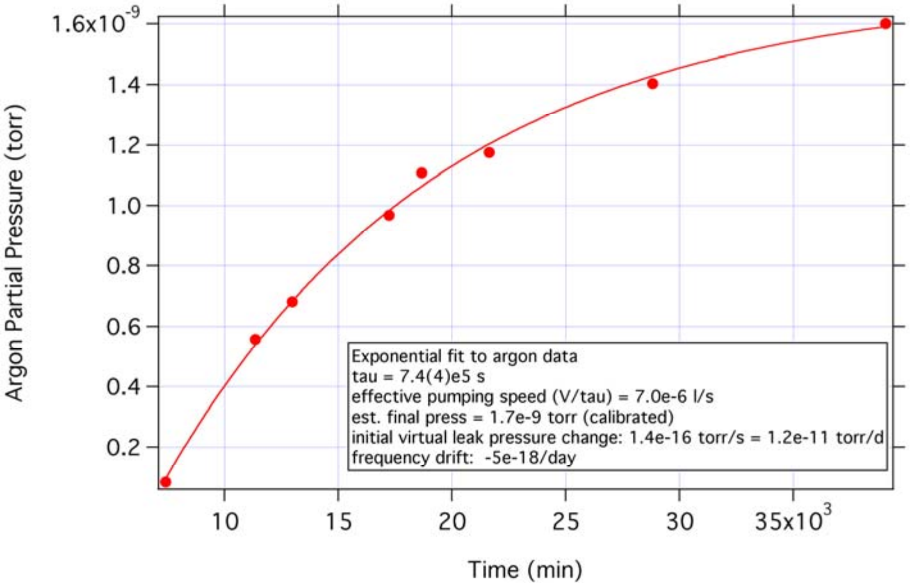

Figure 5. Detail of the argon pressure evolution. The initial slope would result in a clock shift of -5×10^{-18}/day and the exponential fit gives a time constant of about 9 days.

CONCLUSIONS

Compensation of the ion-number-dependent frequency shift has resulted in a 10-fold improvement in long-term stability of the multi-pole LITS atomic clock. A comparison over a 9-month period between the compensated multi-pole LITS-9 and the laser-cooled primary standards showed a fractional frequency deviation of less than 2.7×10^{-17}/day. A subsequent stability evaluation showed that possible residual instabilities could be due to fluctuations in background gas pressure. Initial tests indicate that better background pressure stability can be obtained with a getter pump as compared to the current "flow-through" system that uses a turbo-molecular pump. The tests also indicate that the evolution of non-getterable gases should not limit clock stability at the present performance level. LITS9 is in the process of being converted to use a sealed getter-only vacuum system. Ongoing tests will determine the mean-time between getter activations in this system and whether this maintenance cycle is longer than the current diaphragm fore-pump maintenance cycle of about 18 months.

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