# Improvements to JPL's Compensated Multi-Pole Linear Ion Trap Standard and Long-Term Measurements at the $10^{-16}$ Level

E.A. Burt, W.A. Diener and R.L. Tjoelker
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109-8099, U.S.A.
Email: eric.a.burt@jpl.nasa.gov

***Abstract*--The Multi-pole Linear Ion Trap Standard (LITS) being developed at the Jet Propulsion Laboratory (JPL) has demonstrated excellent short and long-term stability. The technology has now demonstrated long-term field operation providing a new capability for timekeeping standards. Recently implemented enhancements have resulted in a record room temperature microwave line Q of $5x10^{12}$, a short-term fractional frequency stability of $5x10^{-14}/\tau^{1/2}$ and reduction of the combined sensitivity to the primary LITS systematic effects below $5x10^{-17}$ fractional frequency. Initial comparisons to JPL's cesium fountain clock show a systematic floor of less than $2x10^{-16}$. The multi-pole LITS at JPL has been operating continuously and unattended since October, 2006 and is used as the frequency reference for the JPL geodetic receiver known as JPLT, enabling comparisons to any clock used as a reference for an IGS site. Initial comparisons with UTC over a 6-month period show a frequency deviation equivalent to less than $2.5x10^{-17}$/day. In the capacity of a stand-alone ultra-stable flywheel, such a standard could be invaluable for long-term timekeeping applications in metrology labs while its simplicity and robustness make it ideal for space applications as well.***[*]

## I. INTRODUCTION

Continuously running frequency standards with state-of-the-art frequency stability are required for timekeeping and deep space tracking applications. Doppler spacecraft tracking, VLBI, and radio science activities require high frequency and time stability to accurately locate and direct space craft, precisely time send and receive signals, or to correlate signals received in different locations. Linear Ion Trap Standards (LITS) developed at the Jet Propulsion Laboratory (JPL) have demonstrated excellent short [1, 2] and long-term stability [3] and have also demonstrated long-term field operation. The relative insensitivity to the second-order Doppler shift using a multi-pole linear ion trap configuration [4] has resulted in a Hg+ frequency standard with excellent long-term stability [5]. It has been shown that sensitivity to the second-order Doppler shift can be further reduced by introducing a small magnetic inhomogeneity [6]. In this paper we will review this technique as well as other methods used to further reduce the primary multi-pole LITS systematic sensitivities. We will then show the results of the first long-term comparisons made between this advanced multi-pole LITS and UTC as well as other high performance standards. We will show that this version of the multi-pole LITS standard provides a new capability for timekeeping and serves as an unambiguous performance reference of other very stable atomic standards and global time and frequency transfer methods.

## II. THE MULTI-POLE LITS: CONFIGURATION AND PAST PERFORMANCE

The multi-pole LITS evolved from its predecessor, the quadrupole LITS [1], in an effort to improve LITS long-term stability [7, 8]. Subsequently the multi-pole LITS has been further modified and the characterization of these modifications is the subject of this paper. The configuration of this advanced multi-pole LITS has been described in detail elsewhere [6]. It consists of a conventional quadrupole trap (where ion loading, state selection and state detection take place) and a multi-pole trap (where the sensitive microwave interrogation takes place). After loading and state selection, ions are "shuttled" into the multi-pole trap by varying the relative trap DC biases. After microwave interrogation, ions are shuttled back to the quadrupole trap for state detection. This configuration not only takes advantage of the reduced second-order Doppler shift in the multi-pole trap, but also separates microwave interrogation from the various perturbations associated with the loading region. Component choices were dictated by the requirement for long-term operation and simplicity. No lasers, cyrogenics or microwave cavities are employed in the design.

The systematic sensitivities of the multi-pole LITS are summarized in [6]. The largest of these are ion-number-dependent effects, the second-order Zeeman shift and the pressure shift due to collisions between trapped mercury ions and the background buffer gas. The source of each of these – the number of ions trapped, the average magnetic field in the interrogation region and the background pressure – are not

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actively controlled for simplicity and operational robustness. An early version of the multi-pole LITS delivered to the US Naval Observatory (USNO) known as LITS-8 has already demonstrated outstanding long-term performance with a drift of less than $2x10^{-16}$/day relative to the USNO master clock [5]. LITS-8 has also run continuously for periods of up to 1 year without intervention. The multi-pole LITS has previously demonstrated a short-term performance of $7x10^{-14}/\tau^{1/2}$ [9] (the older quadrupole LITS demonstrated a short-term performance of $2x10^{-14}/\tau^{1/2}$ [1, 2].)

Two versions of the multi-pole LITS have been developed: LITS-8 delivered to USNO in 2002 and LITS-9 operating at JPL. Enhancements to and characterization of LITS-9 long-term performance is the subject of this paper. A smaller third multi-pole standard is being developed for possible space flight applications [10 – 12]. A very small physics unit has recently been constructed using a sealed vacuum system showing excellent signal to noise and short-term performance [12].

## III. ION NUMBER DEPENDENT EFFECTS

There are at least three ways that varying the trapped number of ions can change the clock frequency [13]. First, as ion number is increased, space charge repulsion pushes the ions further out radially and axially in the trap where they experience a larger amplitude of the trap rf field. The mechanism known as "rf heating" is thought to cause increases in ion temperature. A higher temperature means a larger average velocity squared and therefore a larger second order Doppler shift. Since the second order Doppler shift scales as $-\langle v^2/c^2\rangle$ where v is the ion velocity and c is velocity of light, the shift has a negative slope with increasing ion temperature. Second, due to the same increase in rf exposure there is increased ion "micromotion" that also increases the average velocity squared and the second order Doppler shift. Third, as the ion cloud increases in size it also experiences a different average magnetic field and an associated change in the second order Zeeman effect. While this change is small, it can be comparable to the second order Doppler shift change. Since the gradient of magnetic field inhomogeneities can in principle have any slope, the sign of this third effect can also be positive or negative with respect to ion number. While the sensitivity of the second order Doppler shift to ion number has been known for some time, the magnetic contribution has only been characterized more recently [14].

### *A. Ion Number Dependence in LITS-8*

To measure ion number dependence, the number of ions trapped is often changed by varying one of the trap parameters that lowers the trap potential. More recently the ion number was also varied in LITS-8 by changing the mercury oven temperature, reducing the background neutral mercury resevoir from which ionized mercury is drawn [13]. Both techniques show about 1 mHz of frequency shift (corresponding to a fractional frequency shift of $2.5x10^{-14}$) for a 30% change in ion number. Both LITS-8 and the unmodified LITS-9, which is virtually identical to LITS-8, show the same dependence on ion number indicating that the magnitude of the effect is inherent in the design.

During its 4-year history of operation at USNO, LITS-8 has exhibited a strong correlation between ion number and frequency. To the extent that we are able to reduce sensitivity to ion number the overall stability of the clock will be improved.

### *B. Modeling Ion Number Dependence*

To gain a better understanding of ion number effects and to explore possible methods for reducing clock sensitivity to them, we built a numerical model of the magnetic fields in the trap region that accounts for both coils and magnetic shields. Since field inhomogeneity is expected to be greatest at the interface between the quadrupole and multi-pole traps, we add to the model an auxiliary ("AUX1") coil at this location for the purpose of modifying field gradients there. The details of the model are described in [13]. Here we only summarize the results.

As ions are added to the trap, the size of the cloud will increase either axially, radially or both due to space charge repulsion. Our model reproduced the approximate 1 mHz shift in clock frequency with a 30% change in ion number with the AUX1 coil off. With the coil on, the model predicted that we should be able to change both the magnitude and sign of the shift. For a particular value of the coil current the shift was completely cancelled, suggesting the use of this coil as a compensation mechanism.

### *C. Changing Ion Number Dependence: Tuning the Magnetic Field*

To test the predictions of the model, an auxiliary coil ("AUX1") was installed at the quadrupole/multi-pole trap interface and frequency vs. ion number was measured for several different coil settings. Good qualitative agreement was found between the model and the measured data as well as a confirmation that the sign and magnitude of the shift could be altered. The curvature and magnitude of the modeled frequency vs. ion number traces are different for the ion cloud expanding in the radial direction than for expansion in the axial direction. The measured data is consistent with cloud expansion primarily in the radial direction.

Fig. 1a shows the frequency shift for a 20% change in ion number with AUX1 off (compensation off) and Fig. 1b shows the frequency shift with AUX1 tuned to a value that gives minimal shift (compensation on). With AUX1 off the shift is -950(26) µHz. With the coil on at the prescribed value, the shift is reduced by about a factor of 15 to -64(19) µHz.

Subsequent tuning reduced this further to +22(24) μHz or a fractional frequency shift of < $+5.9 \times 10^{-16}$. The ion number is typically stable to about 1% over long periods (days or longer), resulting in a stability floor for ion-number effects of < $3 \times 10^{-17}$ with this compensation mechanism in place.

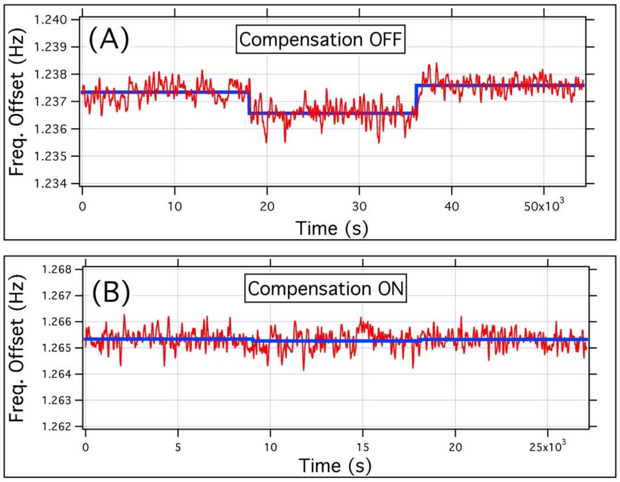


Figure 1. Frequency differences between LITS-9 and a hydrogen maser with compensation (a) disabled and (b) enabled. In each case during the midle third of the data the ion number was reduced by 20%. The greatly reduced sensitivity to ion number changes with compensation turned on is apparent in (b).

Degaussing the shields changes the overall field offset, but not the qualitative behavior of the shift. Since external field fluctuations result in less than a 2 μHz frequency shift as seen by the (magnetically shielded) ions and the current source for AUX1 is at least as stable as the C-field current source, we expect that once the magnetic shields are degaussed, the optimal AUX1 setting should remain fixed.

### *D. Estimating the Number-Dependent Second-Order Doppler Shift in the 12-Pole Trap*

The model can also be used to determine what current in AUX1 will give the most uniform field. Setting AUX1 to this current and measuring the ion number shift provides an estimate of the number dependent second order Doppler shift with no magnetic contribution. The results of this measurement revealed a second order Doppler shift in the multi-pole trap with the expected negative sign as ion number is increased. The magnitude was -2 mHz (empty to full), significantly smaller than that found in the original quadrupole trap, but significantly greater than the sensitivity measured in the compensated multi-pole system (~ 0.2 mHz) [13].

## IV. REDUCING THE PRESSURE SHIFT: NEON BUFFER GAS

The next largest systematic sensitivity, after the second order Doppler shift, is the pressure shift due to the background inert buffer gas used to cool the ions. Previously helium was used, but at $8.9 \times 10^{-9}$/torr, neon reduces this sensitivity by a factor of three [15, 16]. In addition neon is heavier than helium making it a more efficient buffer gas allowing operation at a factor of two lower pressure. For these reasons, the helium buffer gas system in LITS-9 was replaced with one based on neon. Neon delivery is accomplished with a capillary leak thereby eliminating the power and heat load associated with the previous heated quartz leak used to deliver helium. With pressure stable at 1% this corresponds to a fractional frequency stability of $4 \times 10^{-17}$. All other systematic sensitivities are significantly smaller so the combined stability floor for the compensated multi-pole LITS is currently expected to be less than $5 \times 10^{-17}$.

## V. IMPROVING SHORT-TERM STABILITY: LAMP DUTY CYCLE CONTROL

Improved short-term stability allows the clock to integrate down to its stability floor faster. A slight improvement in the multi-pole LITS short-term stability was obtained by changing the lamp operating mode. Previously the best quadrupole LITS short-term stability measured was $2 \times 10^{-14}/\tau^{1/2}$ [1, 2] and the best short-term stability measured in the multi-pole LITS was $7 \times 10^{-14}/\tau^{1/2}$ [9]. The short-term performance of the clock is given by:

$$\sigma_y(\tau) \propto \frac{T_c^{1/2}}{f_0 T_r SNR \, \tau^{1/2}}, \qquad (1)$$

where $T_c$ is the time to execute one complete cycle of the clock, $f_0$ is the clock frequency, $T_r$ is the interrogation time, *SNR* is the signal-to-noise ratio of the clock signal and $\tau$ is the averaging time (overall constants of proportionality have been left out). In addition to a simple increase in *SNR*, increasing $T_r$ will result in a larger atomic line $Q$ ($Q = f_0/\Delta f = f_0 T_r$.) An increase in $Q$ without degradation in *SNR* will improve the short-term stability.

To avoid an undesirable light shift the original quadrupole LITS operated with the lamp in a dim state during the sensitive microwave interrogation. Lamp output is largely determined by temperature, which is in turn controlled by the bright/dim lamp duty cycle. For each lamp there is an optimal duty cycle. However, requiring that the lamp be dim during microwave interrogation is no longer a requirement in the multi-pole trap where ions are shuttled between the region where the lamp performs state selection and detection to an entirely separate region where microwave interrogation takes place. Setting the lamp to operate at its optimal duty cycle, $T_r$ can be increased in multiples of the lamp cycle time limited only by the ion coherence time. The normal lamp cycle time is 8-12 seconds with $T_r$ set to 6-10 seconds. Using this new mode of operation we achieved a $T_r$ of 30.5 seconds with no degradation in *SNR*. With the current *SNR* and this cycle time we predict an improvement in short-term stability to about $6 \times 10^{-14}/\tau^{1/2}$. Longer interrogation times such as these also reduce aliasing noise [18] from a limiting $7\text{x}10^{-14}/\tau^{1/2}$ to a non-limiting $3\text{x}10^{-14}/\tau^{1/2}$.

For $T_r$ > 30 seconds the *SNR* began to degrade due to ion decoherence, yet as shown in Fig. 2 we were easily able to observe a $T_r$ as long as 65 seconds resulting in an atomic line $Q$ of $4.7\text{x}10^{12}$. We believe this is the highest line $Q$ observed in a room temperature microwave atomic transition and within a factor of two of the record atomic microwave line $Q$ measured in a cryogenic laser-cooled $Hg^+$ clock [17].

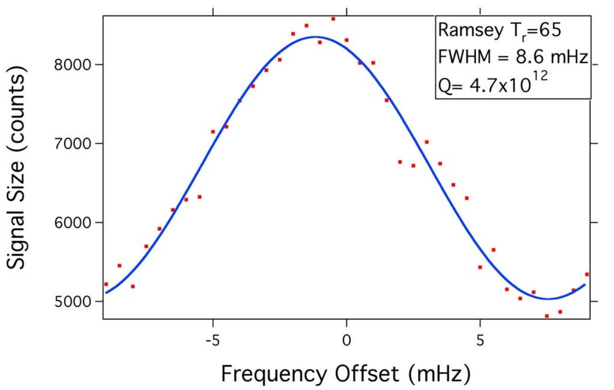


Figure 2. Narrowest LITS line width of 8.6 mHz obtained by setting $T_r$ = 65 seconds and using the lamp operating mode described in the text.

## VI. SHORT-TERM STABILITY MEASUREMENTS

To achieve the optimal short-term stability that LITS-9 is now capable of, it is configured with a hydrogen maser as its local oscillator (LO). Since maser frequency noise improves with averaging times as high as $10^4$ seconds, long LITS interrogation times of the type described in the previous section are possible (this is not the case, for instance, when we use a quartz crystal as the LO.) To measure this stability we compare LITS-9 against three other standards: LITS-8 before it was installed at USNO and before upgrades to LITS-9, another hydrogen maser, and JPL's laser-cooled cesium fountain [19].

Fig. 3 shows the Allan deviation of comparisons between LITS-9 and the three standards just mentioned. For data comparing LITS-8 and LITS-9, both clocks were independently characterized against a hydrogen maser as running at about $1.2\text{x}10^{-13}/\tau^{1/2}$, so in this pair data, a square root of 2 has been removed. The run was terminated because of time constraints on the LITS-8 delivery, but for averaging times up to $10^5$ seconds it integrates down to about $4\text{x}10^{-16}$ and shows no sign of drift.

The comparison between the upgraded LITS-9 and a hydrogen maser shows the improved short-term stability. For times < 30 seconds the noise is due entirely to the maser LO (LITS-9 only steers the maser output every 26.5 seconds.) For times > 30 and < $10^4$ seconds the LITS-9 control loop action is apparent in the curvature of the Allan Deviation slope and the noise is due to a combination of the LITS-9 noise and the control loop noise. By $10^4$ seconds the noise is due to a combination of LITS-9 and the maser, but shortly after that the maser drift will dominate. At $10^4$ seconds this maser had a stability of $5\text{x}10^{-16}$ (measured separately). The combined stability of the maser and LITS-9 at $10^4$ is $7.5\text{x}10^{-16}$ so the stability of LITS-9 at this time is $5\text{x}10^{-16}$ as well. From other measurements we know that LITS-9 exhibits white frequency noise. We therefore expect it to integrate down as $\tau^{-1/2}$ and so the short-term stability of LITS-9 with the new lamp operating mode is $5\text{x}10^{-14}/\tau^{1/2}$.

Measurements against JPL's cesium fountain clock are on-going as that standard has recently been installed in the Frequency and Timing Laboratory at JPL. Comparisons to the fountain are very desirable since fountains have the potential to be far more stable in the long-term than masers. To date however the best comparisons to the fountain have occurred on a 10-day time scale. Over longer periods we observe systematic changes in frequency at the $10^{-15}$ level. However, within runs of 30 days or more there are 8-10 day periods of better frequency stability. The best of these is shown in Fig. 3. During this run the fountain had a short-term stability of $1.6\text{x}10^{-13}/\tau^{1/2}$ so the noise in the Allan deviation is largely determined by the fountain. But it is notable that this noise integrates down to $2\text{x}10^{-16}$.

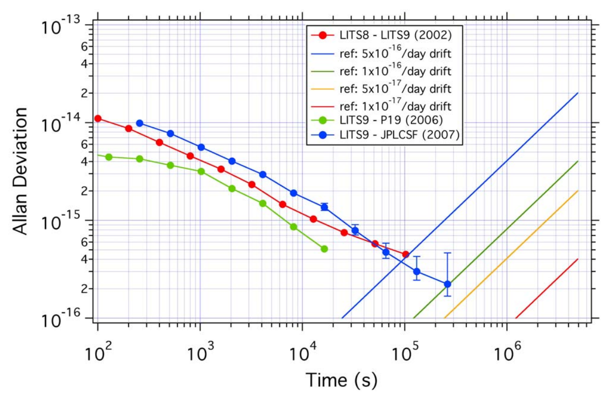


Figure 3. Allan deviation for three comparisons: LITS-8 vs. LITS-9 before LITS-9 was upgraded (red with circles), LITS-9 vs. a local maser (green with circles), and LITS-9 vs. the JPL cesium fountain (blue with circles). The straight lines with no circles represent various drift rates for reference as indicated in the legend. Error bars are shown only for the LITS-9 vs. fountain data for clarity and correspond to 68% confidence intervals.

## VII. LONG-TERM COMPARISONS

Ultimately long-term comparisons will be made with another colocated multi-pole LITS or with the JPL fountain. Until then, the best mechanism that we have for gauging the long-term behavior of LITS-9 is by comparing it to ultra-stable frequency references at other metrology labs using GPS Carrier Phase Time Transfer (GPSCPTT). Careful comparisons between hydrogen masers for times in excess of $10^5$ seconds using GPSCPTT have been made [20], but individual masers can drift on this time scale so it is not clear from this data whether the clocks or the link limit the measurement at the longest times. A possible exception to this is the comparison between the USNO and NIST maser means [24], which are each known to have long term drifts relative to UTC with magnitudes of $2\times10^{-17}$/day or less [25]. While the Allan deviation reaches $7\times10^{-16}$ with an uncertainty just below $10^{-15}$ at $3\times10^{6}$ seconds. This data is suggestive that comparisons below $10^{-15}$ can be made using GPSCPTT, but it is not long enough to determine whether the clocks or GPSCPTT limit the comparison at the longest time. More comparisons are needed between ultra-stable clocks on time scales > $10^{6}$ seconds before conclusive statements can be made about GPSCPTT limitations on this time scale. However while it may be difficult to measure clock stability at the $10^{-16}$ level with GPSCPTT, if comparisons can be made for times longer than $10^{6}$ seconds, this method can be used to make useful conclusions about relative drift.

### *A. GPS Carrier Phase Time Transfer*

By making LITS-9 the reference for the geodetic timing receiver (an Ashtech Z12t) whose designation is JPLT, we can compare LITS-9 to any other standard that is used as a reference for another timing receiver. NIST, USNO and PTB maintain geodetic timing receivers known respectively as NISA, USN3 and PTBB. In the same order, these receivers are referenced to UTC(NIST), UTC(USNO) and UTC(PTB) making continuous comparisons between LITS-9 and these standards possible.

GPSCPTT data is processed using the JPL-developed GIPSY (GPS-Inferred Positioning SYstem) analysis code. Precise Point Positioning along with JPL's precise satellite orbits are used in the analysis. A comparison from MJD 54015 (October 7, 2006) through MJD 54071 (December 2, 2006), about 2 months, was reported in [13]. Here we extend this measurement to MJD 54225 (May 5, 2007), about 7 months total. During this entire comparison LITS-9 was operated continuously with no intervention and all data presented is from one continuous run.

GIPSY analysis produces raw phase residuals. Day-boundary discontinuities, common to GPSCPTT (for example see [20]), are removed by equating the slope of the phase after the day boundary to that before. Typically the mean day boundary correction is several picoseconds and has a gaussian distribution with an RMS of about 500 picoseconds. Occasionally (about once or twice per month) discontinuities or drop-outs in GPS data are found at non-day-boundaries. These are corrected in the same way after verifying by local maser comparisons that LITS-9 performance was nominal at these times. Once discontinuities are removed, a straight line is removed from the phase data by matching the starting and ending points. This slope in phase corresponds to the frequency offset that the LITS operates at by virtue of its C-field value. Finally frequency residuals are calculated as the first difference of the processed phase data. No drift is removed from the frequency data.

### *B. LITS-9 vs. UTC(k) Using GPSCPTT*

Except where noted, all data shown in this section will refer to the aforementioned 7 month period. LITS-9 is the reference for the receiver JPLT so for the purpose of the present discussion the two will be considered synonymous. Similarly NISA, USN3 and PTBB will be taken as synonymous with UTC(NIST), UTC(USNO) and UTC(PTB) respectively. Since the reference standard for GPS is UTC(USNO), raw phase residuals in GIPSY-processed data are STATION(k)-UTC(USNO). Therefore, to obtain phase residuals for LITS9-UTC(k) we take the double difference: [LITS9-UTC(USNO)] - [UTC(k)-UTC(USNO)].

To illustrate the procedure, Fig. 4 shows the individual phase residuals as well as the double difference giving the phase difference for LITS9-UTC(NIST) with a straight line (frequency offset) removed. UTC(NIST) is a steered reference - steers occur typically once per month and may partially account for some of the changes in slope apparent in the phase residuals. The excellent tracking between the individual phases is a reflection of the fact that the two references are not drifting with respect to each other. Fig. 5 shows the frequency differences for LITS9-UTC(NIST) derived from the phase residuals.

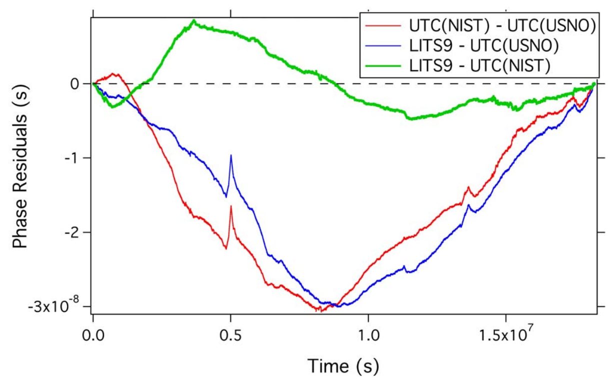


Figure 4. Phase residuals for UTC(NIST) – UTC(USNO) (red), LITS9 – UTC(USNO) (blue) and the double difference LITS9 – UTC(NIST) (green).

When a least-squares fit to a straight line is performed on the LITS9-UTC(NIST) frequency offsets, a slope of $-0.5(4.5)\times10^{-18}$/day is found, indicating no statistically significant drift between the two standards over the measurement period. The reduced chi-squared of the fit is 0.87, which may indicate that the single-measurement uncertainty has been over-estimated. This is likely due to the fact that in the short to medium term the GPS-derived frequency offsets average down as $\tau^{-p}$ where $p > 1/2$. Therefore a single-point deviation will over-estimate the deviation of the data set as a whole if a white noise process is assumed. However a chi-squared of < 1 also indicates that there are no statistically significant higher order processes present and that a straight line is the correct fitting function to use.

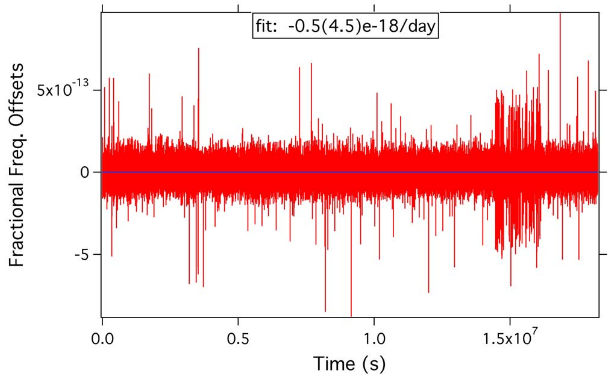


Figure 5. Frequency offsets for LITS9 – UTC(NIST). A fit to a straight line shows no drift within the error estimate.

Using the same analysis method a fit to LITS-9 – UTC(USNO) frequency offsets gives an estimated drift of $4.9(0.5)\times10^{-17}$/day with a chi-squared of 0.77. Note that here as with UTC(NIST), UTC(USNO) is a steered reference. USNO steers are generally smaller than those at NIST and take place more frequently. As a result individual steers are harder to identify in the GPS data.

The reference for PTBB is CS2, a laboratory cesium beam tube frequency standard with excellent long-term stability, but short-term noise that is larger than GPS noise. The frequency comparison here is therefore noisier than the other two. While UTC(PTB) (CS2) is a steered standard, no steers occurred over the time frame of interest and it can be considered free running [21]. The straight line fit to LITS-9 – UTC(PTB) frequency offsets gives the statistically significant drift rate of $3.4(1.7)\times10^{-17}$/day with a larger error estimate than the other comparisons due to the higher noise and a chi-squared of 0.858.

By looking at UTC(USNO) – USNOMM (USNOMM = USNO maser mean) data we can form another double difference that results in LITS-9 – USNOMM [22]. The fit of these frequency offsets to a straight line gives a drift of $4.3(0.3)\times10^{-17}$/day with a chi-squared of 0.888.

Fig. 6 shows Allan deviations for some of the long-term comparisons just described. For reference, the short-term data is included on the graph. Also previous data comparing LITS-8 to the USNO master clock is shown. From the LITS-8 vs. LITS-9 comparison it is clear that the LITS-8 vs. USNO master clock data does not show the systematic floor of LITS-8, but it does show a clear drift term of $\sim1\times10^{-16}$/day [23]. The new compensated LITS-9 vs. UTC(NIST) data also does not show the systematic floor of LITS-9. Here however LITS-9 is showing no statistically significant drift relative to UTC(NIST). The long-term improvement in LITS-9 compared to LITS-8 is evident. As has already been mentioned, the floor of about $1\times10^{-15}$ is not uncommon for measurements involving GPS. The comparison with the USNO maser mean reaches a floor of about $4.5\times10^{-16}$, which is extremely good for these type of measurements, and not typical for GPS comparisons.

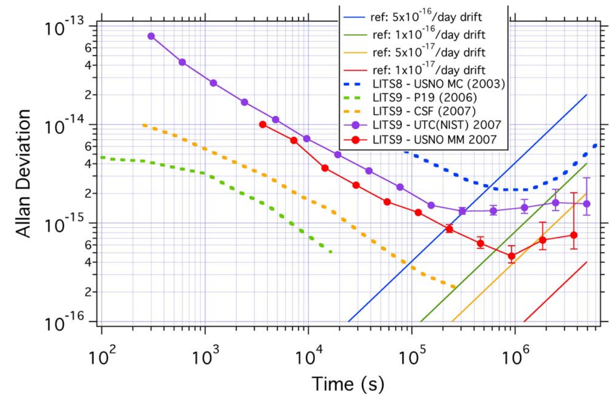


Figure 6. Allan deviation of frequency offsets. The dashed green and yellow lines are the short-term data for reference. Also for reference is the dashed blue line, which shows previous LITS-8 – USNO master clock data. The straight lines show various drift rates. The purple line with circles shows LITS-9 – UTC(NIST) and the red line with circles shows LITS-9 – USNO master clock.

*C. LITS-9 vs. UTC via UTC(k)*

The estimated drift between LITS-9 and the various UTC(k) give values ranging from 0 to $4.9\times10^{-17}$/day. Since each of the UTC(k) are steered references some of the apparent drift can be due to steers in those standards to UTC. Is it possible to get more resolution on how much of the drift can be attributed to LITS-9? The Circular-T document published by the BIPM gives phase differences between UTC and UTC(k) at 5-day intervals. Using this UTC – UTC(k) data we can form another double difference with LITS-9 – UTC(k) to obtain LITS-9 – UTC. We can perform this new double difference using each of the UTC(k) to get different versions of LITS-9 – UTC. In principle if the system has the desired resolution, we should get the same answer (within expected errors) in each case.

Fig. 7 shows frequency offsets derived from this double difference via UTC(NIST), UTC(USNO) and UTC(PTB). As of the writing of this paper, Circular-T data had only been analyzed through MJD 54189. This corresponds to the first 6 months of the 7-month run, however estimates of drift between LITS9 and UTC(k) did not differ outside their respective error estimates between the 6th and 7th month so it is unlikely that the comparison to UTC will change significantly in the 7th month either. Straight line fits to each of these give $2.6(0.9)\times10^{-17}$/day, $2.8(1.0)\times10^{-17}$/day and $2.2(0.8)\times10^{-17}$/day. In contrast to the UTC(k) fits, these fits all had chi-squared values of almost exactly 1. Of course these references are all part of UTC so forming this new double difference is similar to simply taking the average of the LITS-9 – UTC(k) data. However to some degree the individual movements of the UTC(k) should be partially damped in the UTC data. Indeed a consistent picture emerges: whereas the LITS9-UTC(k) data had drift terms that differed outside of their respective error estimates, the LITS-9 – UTC data all *agree* on the drift within their 1-sigma error estimates. A weighted average of the drift rates derived against UTC is $2.5\times10^{-17}$/day, or about a factor of 5-10 improvement over the previous LITS-8 data. It is important to note that while there is no known mechanism for GPSCPTT to drift, it has not been proven that there is no link noise that can appear as a drift on these time scales. Thus, the drift term derived above should be viewed as an *upper bound* for drift of LITS-9 relative to UTC.

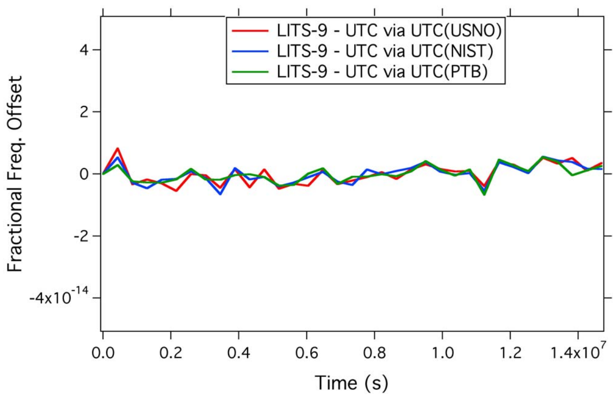


Figure 7. LITS-9 – UTC as calculated through the intermediate references UTC(k) as noted in the legend.

An interesting note on the three comparisons to UTC is the significant amount of correlation between them on the point-to-point (5-day) time scale. However it has already been shown that on this time scale GPS noise is still well above the clock noise. So this correlation should not be taken as LITS-9 noise. More significant is the correlation on 1-month or longer time scales.

UTC is itself a steered reference (it is EAL, the free-running world atomic time, steered to the primary standards). So the drift estimate just derived may still not be representative of LITS-9 performance. In fact if LITS-9 did have a real drift term it is possible that UTC could be steered in the same direction and the LITS-9 drift would be suppressed in comparisons to UTC. However UTC steers are exceptionally small - usually less than $2\times10^{-17}$/day and averaging only $0.8\times10^{-17}$/day over the subject time period. So the worst-case upper bound that one could place on inherent LITS-9 drift would be $3.3\times10^{-17}$/day. However this is relative to EAL and includes the drift of the continuously running standards that contribute to this time scale, which is known to move relative to the primary standards. In either case, this is excellent performance for a continuously running room temperature microwave standard.

### *D. Ion Number Dependence: Another Look Using UTC Data*

There is currently no direct measure of the ion number in the trap. Rather the ion number is indirectly inferred from the signal size, which is the ion resonance fluorescence minus background. In the short-term, which includes all of the number-dependent shift measurements already discussed, this metric represents the ion number faithfully. In the long term both ion number and changes in lamp efficiency can impact signal and signal size is not a good quantitative tool. However it can serve well as a qualitative indication that ion number is increasing or decreasing.

Fig. 8 shows the LITS-8 signal size and frequency offsets between LITS-8 and USNOMM over the first six months of LITS-8 operation at USNO. There is an imperfect but significant correlation between signal size and frequency offset in this data. Fig. 9 shows the LITS-9 – UTC frequency offsets now superimposed with the *LITS-9* signal size over the present 6-month run. Both graphs have the same frequency and relative signal size scales for comparison purposes. The correlation found in the LITS-8 data is strikingly absent in the LITS9 data - further evidence that the number shift sensitivity has been greatly attenuated in LITS-9 using the compensation scheme.

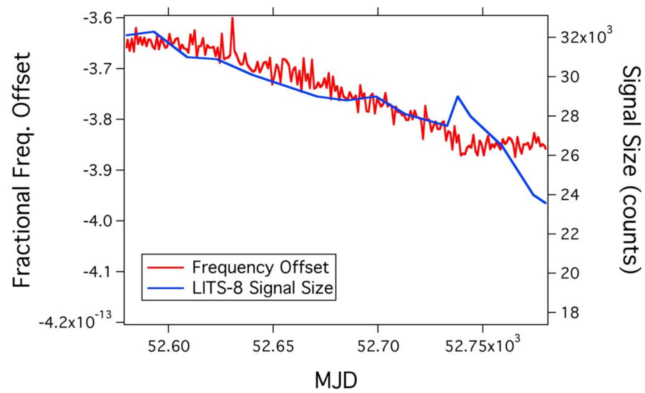


Figure 8. Frequency differences for LITS-8 – USNOMM over the first 6 months of operation at USNO (red) and LITS-8 signal size (blue) over the same period.

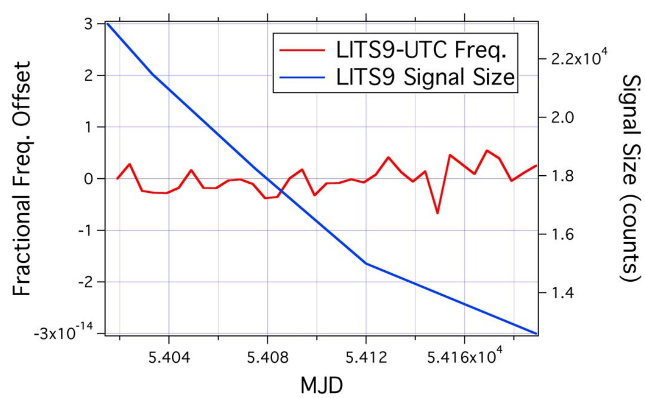


Figure 9. LITS-9 – UTC frequency offsets and LITS-9 signal size over the present 6-month comparison.

### *E. How Well Does LITS-9 Represent UTC? A Comparison*

It is interesting to ask how well LITS-9 represents UTC compared to other high quality representations. Fig. 10 shows frequency differences between the laser-cooled primary standards and TAI as reported in the Circular-T. Accepting the accuracy of the reported measurements, the scatter may be indicative of limitations to sattellite-based global frequency comparison techniques. Fig. 11 shows frequency differences between TAI (equivalent to UTC over the time period of interest) and a) UTC(NIST), b) UTC(USNO) and c) LITS-9. Link noise masks individual clock behavior in the short term, however it is clear that in the long term LITS-9 does very well. The link noise is low enough that for it to still dominate on time scales of 6 months or more implies extraordinary performance on the part of all clocks and ensembles involved.

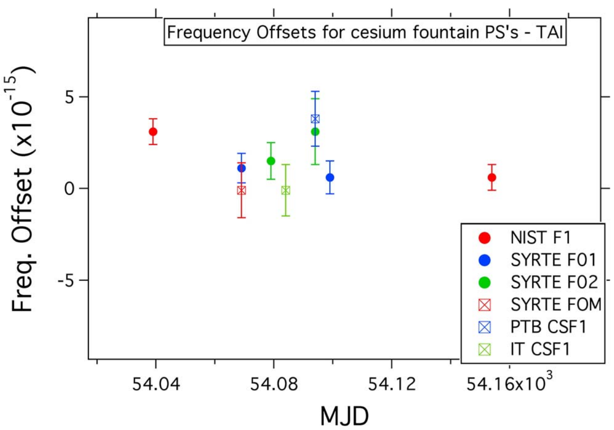


Figure 10. Frequency differences between the cesium fountain primary standards and TAI. All fountain primary standards that reported during the MJD 54019 to 54189 time frame are shown.

## VIII. CONCLUSIONS

We have described a method for compensating the number-dependent second order Doppler shift in the multi-pole LITS and shown that it reduces ion number sensitivity by a factor of 15 or more to $< 3x10^{-17}$. We have also reduced the sensitivity to the buffer gas pressure shift in this clock to below $4x10^{-17}$. All known systematic sensitivities in the clock are now $< 5x10^{-17}$. By using a new mode of lamp operation we have also demonstrated a short-term stability as low as $5x10^{-14}/\tau^{1/2}$ and a record line Q of $5x10^{12}$ for room-temperature microwave standards. Short term comparisons between the upgraded LITS-9 and JPL's laser-cooled cesium fountain show a floor of better than $2x10^{-16}$. Long term comparisons via GPSCPTT show drift terms relative to UTC(k) of between 0 and $5x10^{-17}$/day. Finally Circular-T data was used to that the drift between LITS-9 and UTC is less than $2.5x10^{-17}$/day. To the extent that it is measurable, LITS-9 alone is an excellent continuously running unsteered single standard representation of UTC. In the future we plan to make colocated measurements of two compensated LITS standards and we are investigating how much the size of the standard can be reduced without compromising proformance.

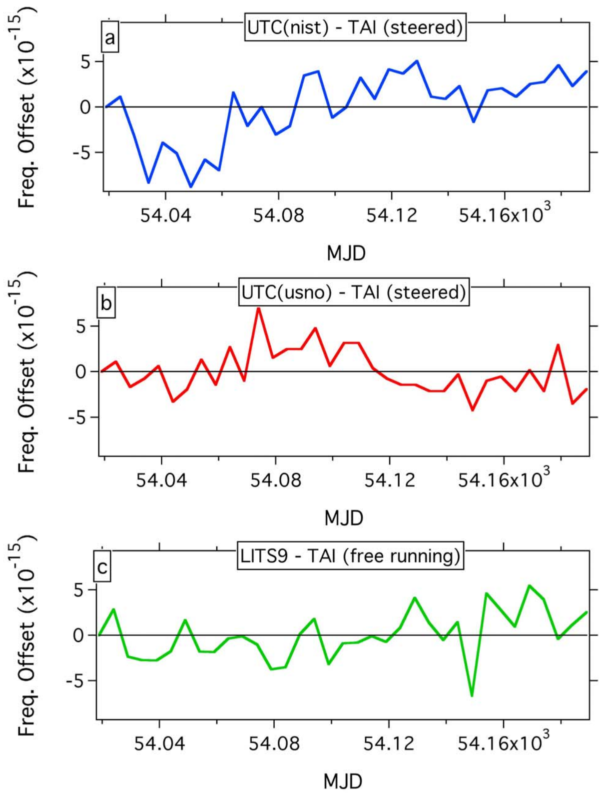


Figure 11. Frequency offsets for a) UTC(NIST) – TAI, b) UTC(USNO) – TAI and c) LITS-9 – TAI.

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