Autonomous Characterization of Clock Drift for Timescale Improvement at the JHU/APL Time and Frequency Laboratory

Mihran Miranian, Gregory L. Weaver, Matthew J. Reinhart
Space Department
Johns Hopkins University, Applied Physics Laboratory
Laurel, MD USA

Abstract—**We have reported on continuous improvements in the capability of our Time and Frequency Laboratory. A substantial portion of our progress in capability was achieved through the incorporation of new clock hardware, improvement in GPS time recovery and coordination of our clocks into the computation of TAI. We have discussed our ensemble of hydrogen maser and cesium beam atomic clocks into a timescale that enables UTC(APL) to be steered within +/- 30 nanoseconds per month of UTC. The propagation of the APL timescale is based on a modified version of the Percival method, requiring regular characterization of each clock's frequency rate and drift.**

Here, we will discuss our results in an autonomous characterization of the individual clocks contributing to the APL timescale. This improvement in our operation has minimized the need for routine operator timescale maintenance and realizes the advantages in clock estimation using frequency, described by J.A. Barnes and D.W. Allan [1]. We will discuss how our approach at characterizing the non-linear drift observed in our hydrogen masers has aided our attempt to discipline the long term frequency drift behavior of quartz ultra-stable oscillators in the space environment. As in previous reports, we will present updated laboratory performance in the form of UTC – UTC(APL).

I. INTRODUCTION

The operational timescale at the Johns Hopkins University, Applied Physics Laboratory (APL) is currently based on a modified version of the Percival method and has been in place for about two years [2]. This method requires periodic observations of the characterization of each clock in order to protect the timescale from frequency changes that could affect its stability. This is especially important when there are a small number of clocks contributing to the evaluation of the timescale. The APL ensemble consists of seven clock sources; two High Performance HP5071A cesium standards, one High Performance Agilent 5071A cesium standard three Symmetricom hydrogen masers and one NASA research hydrogen maser. They are located in the rear of the Time and Frequency Laboratory and are environmentally controlled to +/- 3 °F. This is not an environmental chamber and is subject to perturbations such as when staff enter the lab. Therefore, we must continually monitor the performance of these standards and re-characterize the clocks when necessary. With only seven clocks in the ensemble, each carries an equal weight and it is important that frequency changes be detected as quickly as possible. Even with clock monitoring software, this had become a tedious and time-consuming effort requiring daily evaluation of clock performance. Consequently, it was decided that a self-monitoring and self-correcting timescale algorithm was needed. This paper will describe a new algorithm developed at APL that performs autonomous characterization of clock drifts to improve the APL timescale.

II. TRADITIONAL CLOCK CHARACTERIZATION

Traditional clock characterization methods, like the Percival method, assume that a clock's frequency offset and drift are mostly stationary. Once these parameters have been determined, they are expected to be time invariant and the clock can be entered into the timescale.

Timescale stability is maintained as long as all clocks contributing to the evaluation of the timescale are syntonized. This is called clock characterization and is the basis for producing long term stability of the timescale. Proper characterization of a cesium beam standard usually requires at least 30 days to determine its frequency offset and a hydrogen maser usually requires at least 60 days to determine its frequency offset and drift. Once determined, the clock's frequency offset is corrected to syntonize the clock with the timescale. However, due to the uniqueness of each clock and environmental influences, clocks can experience frequency changes that eventually de-stabilize the timescale. Therefore, clocks must be regularly checked to detect frequency changes.

One method of detecting a frequency change is to simply detect a slope in the frequency difference between the characterized clock and the timescale. If properly characterized, the slope should be zero. If rate or a linear slope is determined, this indicates that the clock is no longer characterized and it should be recharacterized or removed from the timescale.

III. FORMULATING THE APL TIMESCALE

The APL timescale is formulated by averaging the hourly frequencies of the characterized clocks to derive the frequency of the timescale. If the clocks have been properly

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characterized, the frequency of the timescale will be more stable than the frequency of any of the clocks that contribute to its formulation.

All clock measurements at APL are referenced to UTC (APL), which is the output of a micophase-stepper driven by an HP5071A High Performance cesium frequency standard. Therefore, the measurements reflect the variations in UTC (APL) as it is steered to UTC based on monthly reports from the Bureau International des Poids et Mesures (BIPM). Similarly, the characterized clocks also reflect the variations in UTC(APL) and as a result the APL Timescale will be referenced to UTC(APL). The result is the form of a differencing algorithm that provides high sensitivity to individual clock variations to the central tendency of the ensemble with overall stability maintained through the observation by the BIPM. Additionally, because of APL's proximity with the U.S. Naval Observatory (USNO), we share daily GPS common view, time recovery reports that are also used to warn of imminent timescale inaccuracy. Therefore, the stability of the APL timescale is fortified by two external comparison loops of different character and time correction intervals. Of key significance in all aspects of the APL timescale algorithms, both the traditional and the new autonomous described in this report, is their basis in the use of a frequency scale to interpolate time propagation.

The benefit of using frequency in timescale construction has been cited in numerous reports. We chose to call specific attention to the work on the International GPS Service (IGS) timescale as particularly illustrative of how our algorithms work, although we do not implement a Kalman filter in our solution, rather using an iterative regression for individual clock statistics. Nonetheless we can use the nomenclature provided in [3] to provide the mathematical description of our algorithm.

The basis of operation for the timescale formulation follows a state space model for a clock introduced by R.H. Jones and P.V. Tyron and expressed as follows [4];

$$\vec{p}(t_o+\tau)=\phi(\tau)\,\vec{p}(t_o)+\vec{\varepsilon}(t_o) \tag{1}$$

where $\phi(\tau)=\begin{bmatrix}1 & \tau\\ 0 & 1\end{bmatrix}$, $\vec{p}(t)=\begin{bmatrix}rate\\ drift\end{bmatrix}$

and $\varepsilon(t)$ are associated bandwidth limited noise terms.

This individual clock model can then be expanded to a system or ensemble of clocks, 1 to M to form a frequency scale whereby the state-space form is;

$$\Phi=\begin{bmatrix}\phi(\tau)_1 & 0 & 0 & 0\\ 0 & \phi(\tau)_2 & & \\ 0 & 0 & \ddots & \\ 0 & 0 & 0 & \phi(\tau)_M\end{bmatrix} \tag{2}$$

and the individual clock rates and drifts are formed in a sequential column vector, $P(t)$.

Frequency measurements, Y_{MC} of UTC(APL) are made daily in reference to GPS common view recovered time with the USNO. From this data, a new solution for the frequency scale is then estimated at consecutive $\tau = 1$ day for each of j comparisons in the ensemble following the equation;

$$Z_j(t+\tau)=Y_{MC}(t+\tau)-\frac{1}{7}\sum_{k=1}^{7}Y_{MC}(t+\tau)-\left(\phi(\tau)\,\vec{p}^{\,k}(t_o)\right) \tag{3}$$

This process, in effect, detrends each clock with respect to the solution for Z(t+τ) so that, given that each clock has maintained its character, the propagated time will appear as shown in Fig. 1. Notice that the slope in each data trace is nearly parallel and therefore well characterized to the data trace called the APL TIMESCALE. The apparent slope in 'APL TIMESCALE' indicates that a bias or frequency offset exists between itself and the output of UTC(APL).

The central aspect of this frequency scale algorithm and to our success at APL is the concept that shifting the derivative formulation of timekeeping to as simple a state description as possible allows simple and effective processes, such as linear regression for rate (frequency error from the central tendency) and quadratic fitting for drift (aging) to be used effectively when applied recurrently on our small system of clocks. This proves particularly useful in the peculiar mix of hydrogen masers to high performance cesium beam tubes in our laboratory.

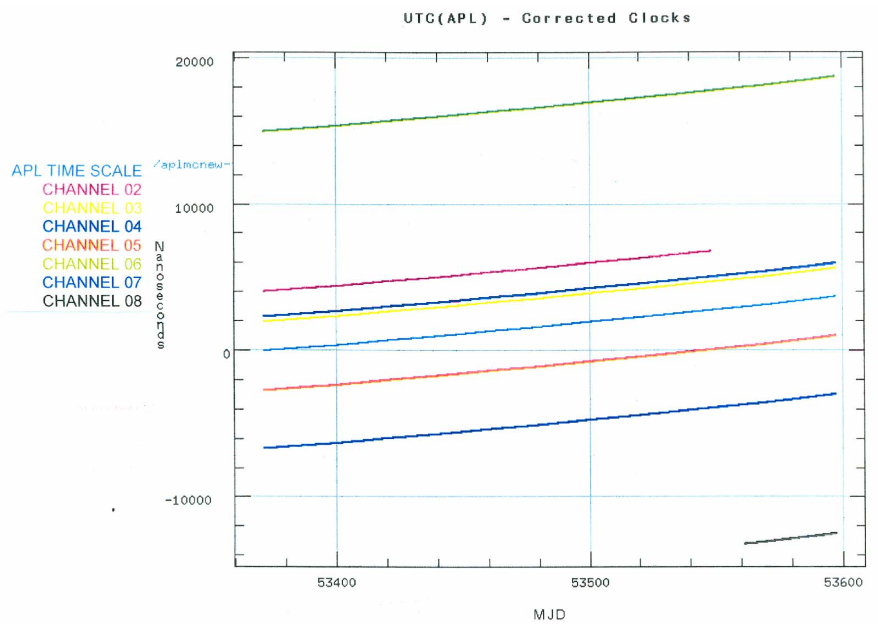

Figure 1. Operational timescale with a comparison to each of the seven APL clocks; refer to TABLE I. for Channel to clock assignment

IV. AUTONOMOUS CLOCK CHARACTERIZATION WITH FREQUENCY

As discussed above, the stability of the timescale is entirely dependent on the accuracy of information on rate and drift for each clock in the state vector, $P(t)$. If the individual clocks were left unchecked over some period of days, the estimate formed in (3) would soon deteriorate as this information aged away from the truth. In this way, routine characterization of the clocks in the ensemble is the process that assures stable operation. Even with only seven clocks in our ensemble, the effort to maintain clock characterization became difficult when performed under routine laboratory conditions. Therefore, an alteration in the basic timekeeping algorithm was installed that essentially closed the information loop by allowing the time keeping algorithm to self-characterize each clock.

The autonomous process analyzes the current and two preceding days of frequency information for each clock to produce a next day prediction of the timescale. In other words, the timescale is propagated one day by the previous three days of clock characterization. The time interval of three days for the autonomous algorithm was set through an optimization procedure that iterated this value from two to ten days and compared the aggregate error of the ensemble clocks' syntonization or error in rate against the timescale. It is likely that three days emerged as the best value since this is where the drift of the masers begins to adequately contrast with the frequency stability of the high performance cesium beam standards. It is reasonable to think that the best time interval for autonomous characterization should exist around a point of stability cross over between the two types of clocks. It was also discovered that with the addition of precise coordination of clock characterization and timescale propagation, the overall accuracy of operation improved. In this manner, our unique circumstance of clocks, almost equally divided between high performance cesium and hydrogen masers, may assist characterization.

For example, in the APL clock ensemble the high performance cesium beam clocks show mostly long term rate errors such that the algorithm need only determine these variations, best interpolated using linear regression over thirty days of data from the following measurement;

$$Y(t) = \mathrm{h}\,\vec{p}(t) + \eta(t) \quad \text{where} \quad \mathrm{h} = [1 \quad 0], \eta(t) \text{ is a scalar noise process} \tag{4}$$

In contrast, two forms of drift affect the character of the Symmetricomm and NASA research masers. The first is a long term aging component that typically requires sixty days of frequency history to determine, using a quadratic fit. The second is a short term drift variation usually caused by temperature change in the laboratory. Because this frequency variation due to temperature takes place over periods of one to two days, this measurement is best captured as a change in the rate characterization.

Consequently, the measurement is formed as follows;

$$Y(t) = \mathrm{h}\,\vec{p}(t) + \vec{\eta}(t) \quad \text{where} \quad \mathrm{h} = [1 \quad 1], \vec{\eta}(t) \text{ is a vector of noise terms.} \tag{5}$$

Since the quality of the cesium beam standards and masers are contrasting in their inherent stability and sensitivity to laboratory environment, the measurements for each clock type, cesium beam or hydrogen maser, are uniquely defined and the precision for each constituent clock will be subsequently reinforced by the central tendency of the ensemble or resulting timescale. This is observed when comparing the residual RMS error in syntonization between the traditional characterization method used previously by APL and the new autonomous method as shown in Table 1. Keep in mind that a zero value means a perfectly characterized clock to the timescale.

TABLE I. COMPARISON OF CHARACTERIZATION ERRORS

Data Channel #[a]	Slopes of Frequency Differences from Timescale		
	Clock	*Traditional Percival*	*Autonomous characterization*
02	5071 cesium	-0.005	0.000
03	5071 cesium	0.002	0.001
04	5071 cesium	-0.007	0.000
05	Symmetricom H maser	-0.006	-0.001
06	NASA Research maser	-----	-0.002
07	Symmetricom H maser	-0.003	0.002

a. The Symmetricomm H maser at Channel 08 has not been in operation for sufficient time to be included in the comparison between timescale formulation methods

The results in Table 1 show a consistent improvement in clock characterization by the autonomous algorithm by several factors over the traditional method. Since this comparison was formulated from the same set of operational data, this improvement can be best attributed to the rigorous application of characterization through the measurements defined in (4) and (5) over a daily precession of three-day clock characterization data.

V. AUTONOMOUS TIMESCALE PERFORMANCE AND USO EXPERIMENT

As an additional investigation, we chose to include the performance of an APL ultra-stable quartz oscillator (USO) into an experimental version of the timescale, formulated by the autonomous method, to assist in our research toward the disciplining of such an oscillator in the space environment and further test the robustness of the autonomous algorithm. The USO used in this investigation was maintained in a thermal vacuum system at a constant temperature of +12 ^{o}C at pressures of less than 1 μTorr to simulate 70 days of space operation. Fig. 2 is a plot of the USO's frequency history over this time period along with a plot of the running

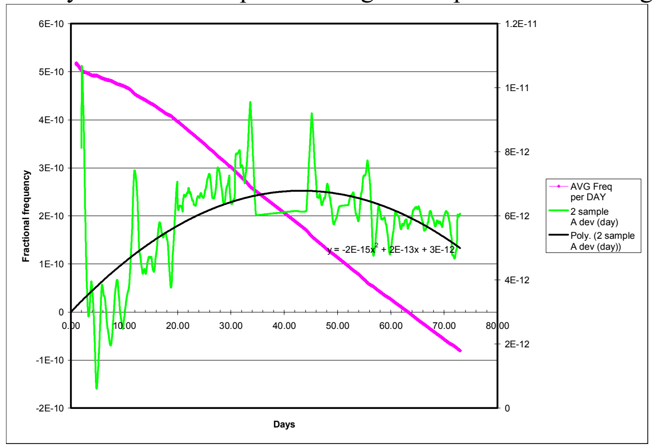

Figure 2. Frequency and drift history of USO used in timescale experiment

two-sample Allan deviation with a one-day time interval. Two aspects of this USO's frequency character are important toward its experimental use in the autonomous timescale formulation. First, the overall rate or syntonization error is several orders of magnitude greater than that of either the cesium bean standards or the masers. Second, the USO shows a complex drift process not well estimated by a quadratic since the drift character is not constant and also not monotonic.

These USO aspects could corrupt the stability of the timescale since their complexity is well outside the characterization of the cesium beam standards (rate only) and the hydrogen masers (mostly constant drift). This is clearly observed in Fig. 3, which is a plot of the clocks of the experimental timescale consisting of three cesium beam standards, three hydrogen masers and the APL USO, at channel 09, in their natural state prior to characterization.

Pleasingly, such corruption was not observed when the autonomous algorithm formulated the experimental timescale, as shown in Fig. 4. In Fig. 4, the USO's complex frequency character is seen as an undulating line against the almost purely linear plots of the experimental timescale and the other six atomic clocks. Also, the USO only skews the resulting experimental timescale, due to its less than optimal characterization, by less than 100 nanoseconds over the 36 days of interpolated time as compared to the operational time scale shown in Fig. 1.

It is important to point out that the experimental timescale in Fig. 4. was formulated in a post process manner, working on the last 36 days of data presented in Fig. 3. It is likely that if the algorithm had been run in its normal operating condition of three day periodic updates for characterization, the complexity of the USO drift would have been sufficiently reduced to remove any apparent skew in the experimental timescale.

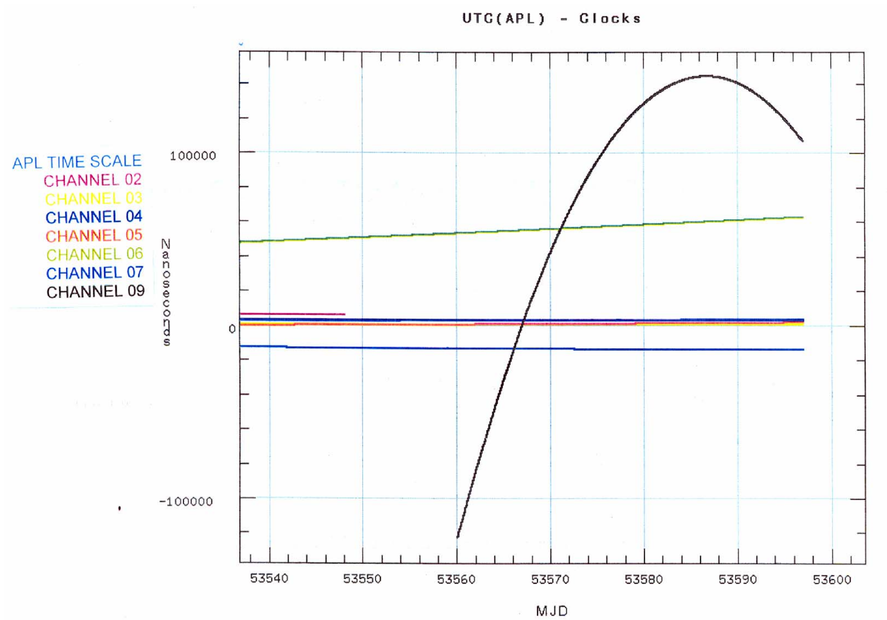

Figure 3. Uncorrected time stability of clocks used in experimental timescale; refer to TABLE I. for Channel to clock assignment

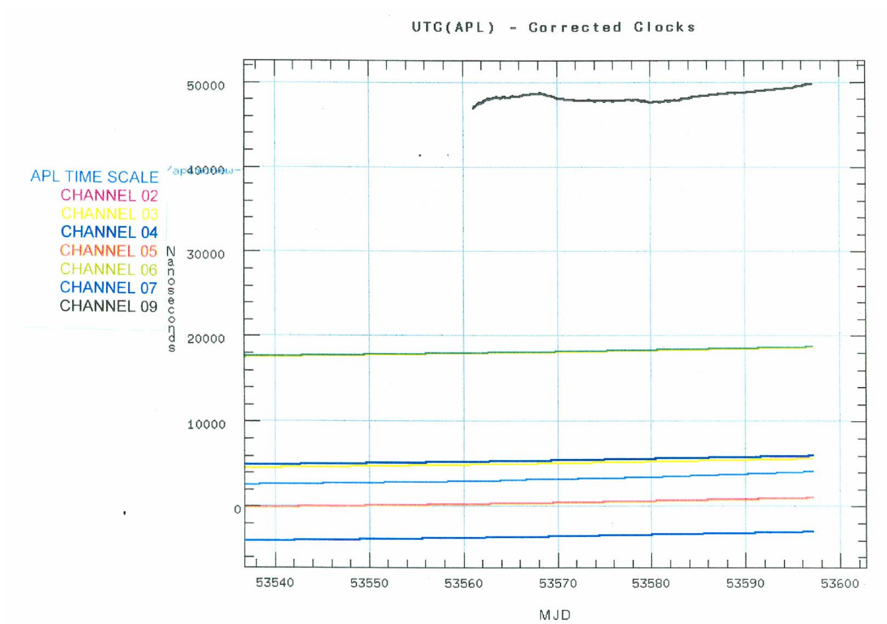

Figure 4. Characterized clocks processed by autonomous algorithm; refer to TABLE I. for Channel to clock assignment

Nonetheless, the results of the experimental timescale are encouraging to our concern toward its ability to maintain stability with a small number of clocks with disparate natural character. It reinforces our work that quartz USO's with the complexity of space environment can be disciplined under an update rate greater than 30 days. In fact, a rough approximation from Fig. 4 indicates that this stability should be at less than 2 μsec over 30 days, which represents nearly three orders of magnitude improvement over the uncharacterized USO time stability.

Finally, we report on the recent performance of UTC(APL) with respect to UTC. As stated earlier UTC(APL) is the steered output of our cesium beam master clock and serves as a reference for the frequency measurement of the APL timescale. The implementation of the autonomous characterization algorithm was at MJD 53371 as indicated in Fig. 5. Since that date UTC(APL) has maintained a steady +/- 30 nsec time stability and anticipates the maintenance of this performance for the foreseeable future.

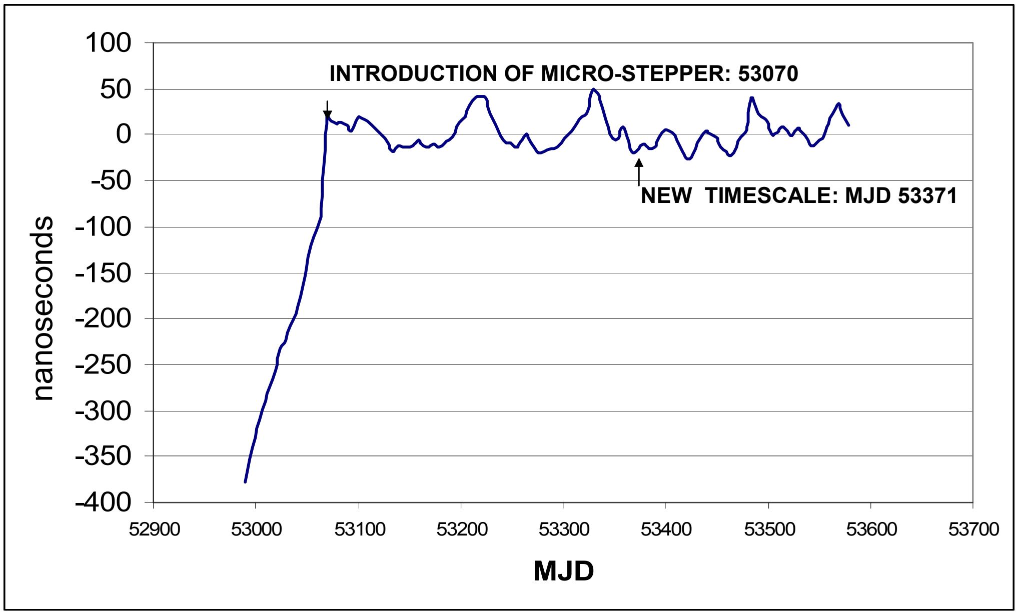

Figure 5. Time stability of UTC(APL), before and after autonomous characterization

VI. SUMMARY AND CONCLUSIONS

We have gained greater confidence in our laboratory's performance this year from the advantages realized by the autonomous characterization of our seven clock ensemble. The new timescale generated from this algorithm reduced the effort for operational maintenance while keeping if not improving UTC(APL) stability. The results of the autonomous algorithm keep UTC(APL) with +/- 30 nsec of UTC and improved the overall characterization of the constituent clocks by several fold. The formulation of the timescale based in frequency characterization has proven robust not only for the small number of clocks but also with our unique mix of three cesium beam standards and four hydrogen masers. The experiment to include a quartz USO further reinforced the benefit of frequency characterization, even with complex, not constant drift aspects. The formulation of the experimental timescale has improved our understanding toward the development of a USO based timekeeping system for space application.

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