Development of a Precise Timescale for Research and Training Purposes

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***Summary*—A timescale algorithm demonstrating a clock ensemble utilizing commercial atomic clocks and multiplexing equipment has been established at the University of Alabama to serve as a testbed for research and student training.**

Keywords—Timescale; Clock Ensemble; Kalman Filtering

I. Introduction

Timescales based on atomic clocks are an integral part of essential global infrastructures such as navigation, telecommunication, and stock exchanges [1]. The practical realization of a timescale relies on using an ensemble of clocks to produce an output more robust than any single clock. Many such timescales generated by the National Metrology Institutes (NMIs) contribute to generate the Universal Coordinated Time (UTC), which serves as a superior reference to which the individual timescales can in turn be steered towards. These timescales use custom designed algorithms to estimate and maintain the timescale output. Examples of such timescales include AT-1 used by the National Institute of Standards and Technology (NIST) or A.1 used by the United States Naval Observatory (USNO) [2,3]. These timescales concurrently provide input to the International Bureau of Weights and Measures (BIPM), where the weighted average of all the inputs from such NMIs are combined based on the performances of the timescales to formulate UTC using a custom algorithm [4]. Timescale testbeds have proven useful not only terrestrially, but also in extraterrestrial settings for better reliability and synchronization, such as the One Clock Ensemble (ONCLE) solution for the Galileo timing system or the timescale used in the receiver clock in the Sentinel-6A satellite [5,6].

The Precision Navigation, Timing, and Frequency (PNTF) laboratory at the University of Alabama is working on designing and developing a local timescale. Presently, we have developed an algorithm based on a Kalman Filtering method that combines the output of individual free-running local clocks to produce an ensemble output, with the general layout shown in Fig. 1 [7]. The goal of such a system in a university setting is to enable research, outreach, and student training in the field of time and frequency. The PNTF laboratory at the University of Alabama has successfully developed and implemented an ensemble algorithm using three atomic clocks and multiplexing equipment similar to that of national timescales, with the motivation of moving towards the realization of a paper clock, or a record of the difference between the ensemble output to a superior reference, such as UTC.

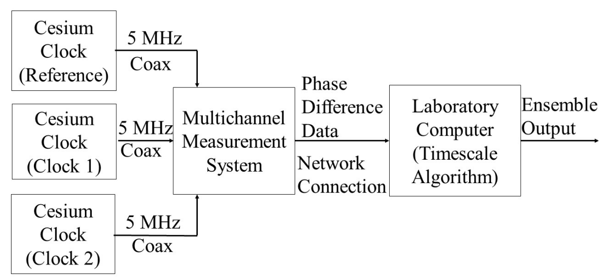

Fig. 1: Block Diagram of the University of Alabama Clock Ensemble

Our clock ensemble has an Allan Deviation stability as low as 2.56e-14 based on accumulated data taken over a period of 33 days. The measurements are currently being continued for longer timescales. However, this algorithm implementation serves as proof-of-concept demonstration and is further scalable; for instance, allowing for expansion by adding more clocks. In addition, important processes related to the computation of ensemble time as an algorithm output as well as the computing interface between the ensemble clocks, measurement systems, and laboratory computers and networks have been validated by the algorithm, enabling a better understanding of system architecture.

The next step towards the realization of a local timescale is to compare our local ensemble directly with that of the Global Positioning System (GPS) time and/or two-way satellite time and frequency transfer (TWSTFT) methods to formulate the traceability to UTC. In addition, due to the proximity of the PNTF Lab with a local Microchip TWSTFT equipped facility approximately 5 kilometers away, we plan to perform the synchronization studies using a fiber network. The efforts to implement these systems are currently underway. Further, we plan to add three Active Hydrogen Masers (AHM) to our clock ensemble in the near future. One of these AHMs will serve as a master clock, the physical output of which will be steered to UTC forming a local precise timescale for education and research purposes.

II. ARCHITECTURE

Presently, our clock ensemble is comprised of three commercial cesium (Cs) standards (5071A) [8], with two serving as member clocks and one serving as a reference unit with the measurement hardware configured as in seen in Fig. 1. The phase of each member clock is compared against the reference clock using a custom designed Multichannel Measurement System. The noise floor of this system was characterized by using two separate channels measuring the same clock signal and using the phase differences between these channels to to calculate the Allan Deviation of the noise floor, shown in Fig. 3. The performance of the Multichannel Measurement System was superior than any individual clock performance observed by a Microchip 3120A noise probe for each clock, affirming that noise measured in the clocks can be attributed to the clocks themselves. The phase differences reported by the Multichannel Measurement System are then sent to a laboratory computer over the network connection. The laboratory computer stores the phase data over the set measurement period, and then uses this data as input to the ensemble algorithm, which analyzes and outputs the ensembled frequency. An example of this ensembled frequency stability output can be seen in Fig. 2.

III. THE ENSEMBLE ALGORITHM

The algorithm used by the clock ensemble is a Kalman Filter utilizing two state equations for each member clock, frequency and frequency drift. These equations can be seen in (1), with F representing frequency offset, D representing frequency drift, and Δt representing sample period.

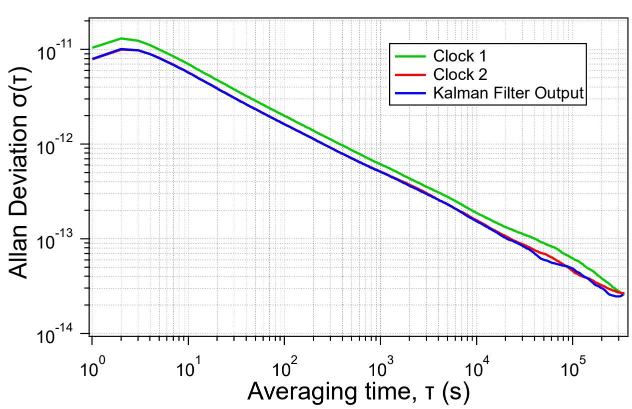

Fig. 2: Allan Deviation of member clocks and Kalman Filter output.

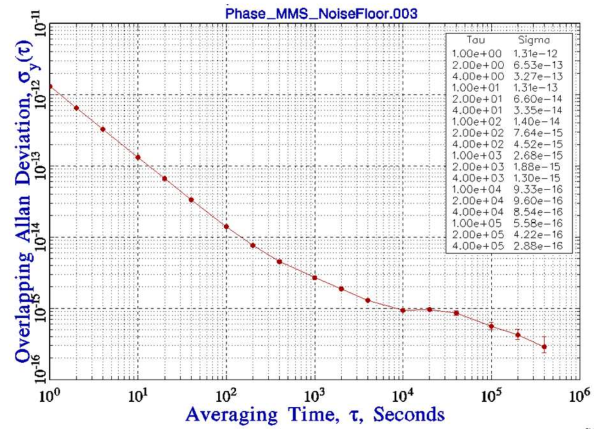

Fig. 3: Noise Floor of Multichannel Measurement System.

$$\begin{matrix} F \\ D \end{matrix} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \quad (1)$$

Our ensemble algorithm follows a typical progression of a Kalman filter, including an estimate of the states of each clock based on the addition of the state equations seen in (1) and the noise processes (referred to as Q in (2)), estimates of the covariance, and the tuning of the Kalman Gain to balance the weight of estimates versus measurements when establishing the Kalman Estimate of the frequency offset and drift of each clock [7]. The equations used to derive the noise process matrix, *Q*, can be seen in (2), where Δt represents the measurement period and components of *Q* are defined by (3). Equation 3 is the Allan Variance of each i^{th} member clock, where *t* is the independent variable of the averaging time for the curve of the Allan Variance and the *q* coefficients are used to achieve a curve of best fit to approximate the Allan Variance.

$$Q = q_{1i}\begin{bmatrix} \Delta t & 0 \\ 0 & 0 \end{bmatrix} + q_{2i}\begin{bmatrix} \Delta t^3/3 & \Delta t^2/2 \\ \Delta t^2/2 & \Delta t \end{bmatrix} \quad (2)$$

$$\sigma_i^2(t) = \frac{q_{1i}}{t} + \frac{q_{2i}t}{3} \quad (3)$$

After the estimates for the frequencies of each clock are compiled by the algorithm, these frequencies combined using a weighted average based on the covariance of the frequency of each clock. The use of covariance as a determining factor for weighting was chosen as due to the ease of accessibility of the value in the algorithm and is fairly static over the measurement period, meaning that it is straight-forward to verify the functionality of the algorithm weighting schemes within the algorithm itself, not requiring external functions used to calculate performance characteristics such as Allan Deviation which could have complicated the verification process.

IV. DISCUSSION/INTERPRETATION

The performance of the individual member clocks are not at par with new commercial units – these clocks were manufactured more than 20 years ago and have degraded with ageing, however the resultant Kalman Filter frequency output shows an effective weighting scheme – as a demonstration of our ensemble algorithm, with the ensemble output largely favoring the superior clock and in some averaging times exceeding the performance of both member clocks. However, the algorithm does show some points that can be improved upon. Seen in Fig. 4 is the frequency offset section of the Kalman Gain for clock 1 over the measure period. The value settles around 0.7, favoring measurement over the state estimates handily. This has led to a reduced ability for the algorithm to filter out transients of the measurement systems and clock outputs. Further characterization of the noise processes over longer measurement periods will allow for a better fit to be ascertained from the use of (2) and (3), creating a more accurate estimate of the noise processes that need to be filtered out by the algorithm. However, this is a successful proof of concept for both the hardware used in the PNTF lab as well as the Kalman Filter used at the core of the ensemble algorithm, creating a starting point for further improvement and research in timescale realization and performance.

Other future improvements will include the addition of three AHMs. Moving forward, our goal is to demonstrate a combined output of three AHMs and three Cs clocks, thus the best performances of AHMs will be utilized in the short-to-medium-term and the Cs clocks will be assigned a larger weight over the long-term with durations of weeks to months, improving our ensemble performance and demonstrating the ability to characterize and utilize multiple species of atomic clocks in the ensemble. In the next configuration, one of the AHMs will serve as a reference clock. In addition, our clock ensemble output will then be compared and synchronized with UTC via the GPS or TWSTFT to form a paper clock. We also plan to do ensemble comparisons with NIST and USNO over time-and-frequency transfer techniques, including the comparisions between UA and Microchip in Tuscaloosa. While creating a national timescale is not the goal of the PNTF lab, these improvements will allow for the PNTF lab to create a timescale with many variables and processes that are present in national timescale laboratories, allowing for meaningful research to be conducted on topics such as time-and-frequency transfer techniques and novel algorithm implementations.

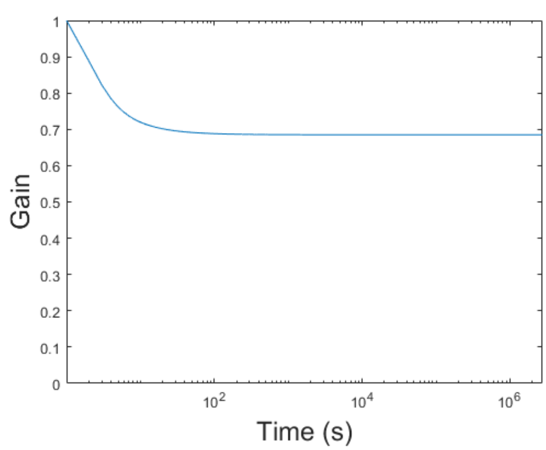

Fig. 4: Frequency Offset Component of Kalman Gain for Clock 1.

The PNTF lab timescale will in the same way provide a robust training platform for the next generation of time keepers. With this goal in mind, the demonstration of this algorithm serves as a starting point. The algorithm can be expanded to a real-time implementation with a larger number of member clocks, comparison to GPS or UTC for the formation of a paper clock, and the capability of steering an output, generating a local timescale. Presently, efforts are underway to implement the algorithm in real time, and a longer measurement period currently being conducted will allow for better characterization of measurement equipment and the establishment of noise floors with improved accuracy and confidence. In addition, there are current efforts to allow for the ability to compare the ensemble time with GPS. These improvements, alongside the ongoing acquisition of AHM clocks and other auxiliary equipment, will enable the realization of a timescale used for research and training purposes.

Once these improvements are implemented, we will explore the novel possibilities of clock ensemble and timescale generation using algorithms based on neural networks and synchronization.

V. Conclusions

The PNTF laboratory at UA has developed a clock ensemble that can be used for both research for novel algorithm improvements, and training and development of future members of the precise time and frequency community. The present algorithm is developed utilizing a two state Kalman Filter with three Cs standards, demonstrating a stability of 2.56e-14 around three days averaging time, with 33 days of continuously collected data. Future improvements, such as the addition of high-performance clocks and GPS synchronization with UTC are underway.

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