

SYMMETRICOM TIME-SCALE SYSTEM

Timothy Erickson¹, Venkatesan Ramakrishnan², Samuel R. Stein³

¹Symmetricom, Inc., Boulder, CO, USA, tierickson@symmetricom.com

²Symmetricom, Inc., Santa Rosa, CA, USA, vramakrishnan@symmetricom.com

³Symmetricom, Inc., Boulder, CO, USA, sstein@symmetricom.com

Abstract: Symmetricom has developed a Time Scale System that incorporates advanced measurement, signal processing, and algorithmic techniques to provide an automated solution suitable for a national time scale. The total system includes two redundant time scale sub-systems with automatic output switching in case of a failure. Each time scale creates a real-time UTC(lab) output including such signals as 1 PPS, IRIG time codes, serial time code, 5 and 10 MHz, NTP, and PTP. The base system supports up to 6 local clocks, which may be either cesium standards or hydrogen masers and additional remote clocks. Input switching of the clocks is used so that failure of an individual clock does not cause a failure of the UTC(lab) output. The time scales use the KAS-2 algorithm to create a free time scale called TA(lab) [1],[2],[3]. A coordinated paper time scale is formed by steering relative to the free time scale using measurements from either the GNSS receiver or Circular-T. The UTC(lab) output is generated by steering a synthesizer to the coordinated time scale. The paper presents the overall system design as well as details of the time-scale algorithm, robustness algorithms, and steering algorithms. Performance data are presented.

Key words: time scale, frequency stability, UTC, Kalman filter.

1. INTRODUCTION

The overall time-scale system, shown in Figure 1, is composed of two redundant time-scale sub-systems that each generate independent versions of UTC(lab). These sub-systems are connected to the users through output switches, so that if the primary time scale fails the backup system takes over the role of providing signals to the users. One switch is used for each of four different signals

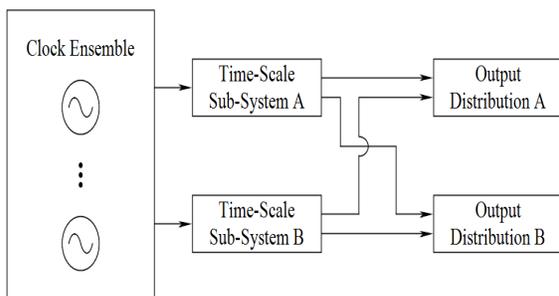


Figure 1: A single clock ensemble provides the reference to two redundant time scale systems

– 1 PPS, 5 MHz, 10 MHz, and IRIG-B time code. NTP and PTP network time protocols are also delivered to users. These protocols are not switched in the event of failure. Instead, the servers transmit their status and users switch to the alternate IP address when a server indicates bad status. Figure 2 illustrates the basic arrangement of a time-scale sub-system.

The UTC(lab) signal is generated from one clock by shifting its frequency in a high resolution synthesizer in order to steer it in time and frequency to be nearly equal to UTC. The time difference between UTC(lab) and UTC is available either directly through GNSS or indirectly from Circular-T. Time differences may be obtained in real time from a GNSS receiver that supports both GPS and GLONASS systems. Time differences may be obtained after the fact from BIPM’s Circular-T. The connection to BIPM can be made either using GNSS common view or two-way time transfer. Common view data are automatically collected from the built in GNSS receiver and used to compute the BIPM common view tracks which are formatted in conformance to the CGGTTS requirements. Two-way time transfer measurements are collected from an optional SATRE modem and formatted in accordance with the ITU-R TF.1153-2 requirements. After a laboratory registers with BIPM, it may email its reports to BIPM and download Circular-T approximately 10 days after the end of each month. When Circular-T is used for steering, the operator must enter the time offsets from the prior month through the user interface so that the time-scale system can calculate and apply the steering correction to the real-time clock.

Although a single physical clock must be used as the reference for the synthesized UTC(lab) signal, a time scale can be used to guarantee continuity of time despite individual clock failures. Thus, reference to the synthesizer

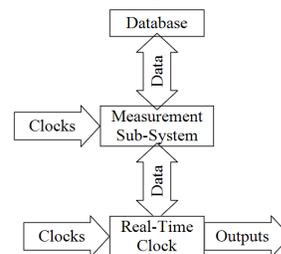


Figure 2: A Time-scale sub-system consists of a real-time clock, measurement subsystem, and database.

is computed relative to the free running time scale. When it becomes necessary to switch to an alternative reference clock, the synthesizer's frequency is corrected based on the known offsets of the two physical clocks relative to the time scale. The time error that results from the reference clock switch is removed by the control loop that steers UTC(lab). Symmetricom uses the KAS-2 time scale algorithm, which it has developed over the last 20 years. This algorithm is executed in two steps. First, optimum estimates of the time, frequency, and aging differences between the clocks are estimated using the Kalman filter approach developed by Tryon and Jones [4]. Second, the corrections of each clock with respect to the time scale are computed by requiring that the weighted noise impulses that perturb each clock sum to zero [2]. Since the clocks have three different noise processes, there are three weights per clock, which allows the time scale to be optimized simultaneously in the short, medium, and long term. In addition to reliability improvement, the frequency stability of UTC(lab) is improved in proportion to the square root of the number of clocks by steering it to the coordinated time scale.

It is important to archive results in any time scale system. The Symmetricom Time-Scale System includes a server with a RAID 5 array of three hard disks to store measurements and computational results with minimal chance of data loss. Clock measurements are stored in a SQL database every second. There are eight measurements per record including six free running clocks, the local UTC(lab) and the redundant UTC(lab). The reference for all measurements is a synthesizer contained within the measurement system. Time scale values are computed and stored every five minutes. The coordinated time scale is steered relative to the free time scale using the state-variable feedback technique. Twelve computed values are stored per record including the free time scale, the coordinated time scale, 6 free running clocks, UTC(GNSS), UTC(GPS), and UTC(GLONASS), and the backup UTC(lab). The reference is always the local UTC(lab). Enough disk space is provided for data storage for 10 years.

In order to steer the coordinated time scale, the time and frequency states are computed using a least-square fit to either the GNSS or Circular-T data. Steering occurs every five days, on MJDs ending in 1.5 and 6.5 according to the BIPM recommendation [5]. The time constant is user selectable from 5 days to as long as desired. The physical output, UTC(lab), is steered to TC(lab) using the same state-variable feedback as the coordinated time scale steering. The time constant is short (typically 20 minutes) and the states are derived from the measurements of UTC(lab) and the time scale computation of TC(lab).

2. SYSTEM DESIGN

2.1. Hardware

The time scale of Figure 1 has been implemented in four equipment racks that contain all of the hardware except for four of the clocks in the ensemble. A photograph of the system is shown in Figure 3.

One 12 slot modular chassis contains the real-time clock hardware that computes the free running time scale and the



Figure 3: Photo of a 4 rack dual-redundant time-scale system that supports up to 6 local clocks and an unlimited number of remote clocks

coordinated time scale. It has a synthesizer that steers the output to the coordinated time scale to form the UTC(lab) output frequency. The synthesizer uses one of three clocks selected by a switch as its reference so that the output can continue to be steered to the local coordinated time scale even if one or two reference clocks fail.

A second 12 slot modular chassis contains the modular measurement system which makes phase difference measurements of 8 clocks with a noise floor of $5 \times 10^{-13}/\tau$. The measurement system utilizes the heterodyne technique and maintains the total elapsed phase difference between the clocks for as long as it runs continuously [6]. Measurements are made once each second and are transferred to the real-time clock for time-scale computation. They are also stored in a relational SQL database on an independent server computer. Six of the eight channels are used for clocks in the ensemble while one is reserved for the local real-time clock and the last is reserved for the redundant real-time clock.

2.2 System Operation

The user interface is accessible locally via a monitor and keyboard. It is also available via a network connection. Initial system startup is managed by a configuration file. Once the system is operating, the user can manage the configuration without interrupting system operation. The main configuration items are:

1. *User access administration*
2. *Setting time including leap seconds either via GNSS or manually*
3. *Managing clocks in the ensemble including adding, dropping, setting noise parameters, and setting weights*
4. *Setting steering parameters for the coordinated time scale and the real-time clock*
5. *Switching between manual steering and automatic steering to GNSS*
6. *Selecting data for display on the real-time clock screen*
7. *Extracting data from the database*

8. *Displaying database disk usage and RAID array status*
9. *Viewing the GNSS report and the Clock report*
10. *Observing system errors, designating critical faults, and acknowledging error conditions*

The time-scale system operation is fully automated and requires no local operator. It can be monitored and managed remotely via a network connection. The BIPM clock report, the BIPM GNSS common view report, and the ITU two way report are generated and stored on the system where they are available for download via FTP. Emails and SMS messages are sent whenever a critical fault occurs.

3. ALGORITHMS

3.1. Time Scale Algorithm

A simple, very realistic model for all precision clocks is the perfect integrator. Hydrogen maser, cesium, and rubidium atomic clocks can all be modeled with no more than three states: the phase, $x(t)$, the frequency, $y(t)$, and the frequency aging, $\omega(t)$. The equations of motion that relate the states are

$$\begin{aligned} x(t_{k+1}) &= x(t_k) + \delta y(t_k) + \frac{\delta^2}{2} \omega(t_k) + \varepsilon(t_k) \\ y(t_{k+1}) &= y(t_k) + \delta \omega(t_k) + \eta(t_k) \\ \omega(t_{k+1}) &= \omega(t_k) + \alpha(t_k) \end{aligned} \quad (1)$$

where t_k and t_{k+1} are successive sample times related by

$$t_{k+1} = t_k + \delta. \quad (2)$$

According to this model, the phase of the clock is the integral of its frequency, which in turn is an integral of the frequency aging. In addition, each state of the clock evolves from one time to the next by absorbing or integrating a random shock. The clock has random-walk phase noise (white frequency noise), random-walk frequency noise, and random-walk frequency aging noise. This model is sufficiently rich to describe all precision atomic clocks – active and passive H masers as well as Cs and Rb clocks.

The clocks are measured at each sample time, t_k . We denote these measurements

$$z_{ij}(t_k) = x_i(t_k) - x_j(t_k) + v(t_k) \quad (3)$$

where z_{ij} is the phase difference measurement between the i^{th} and j^{th} clocks and v is the noise perturbing the measurement.

The clock-difference problem is set up by differencing equation (1) for two clocks i and j .

$$\begin{aligned} x_{ij}(t_{k+1}) &= x_{ij}(t_k) + \delta y_{ij}(t_k) + \frac{\delta^2}{2} \omega_{ij}(t_k) + \varepsilon_{ij}(t_k) \\ y_{ij}(t_{k+1}) &= y_{ij}(t_k) + \delta \omega_{ij}(t_k) + \eta_{ij}(t_k) \\ \omega_{ij}(t_{k+1}) &= \omega_{ij}(t_k) + \alpha_{ij}(t_k) \end{aligned} \quad (4)$$

The goal is to estimate the clock difference states given the model of equations (4) and the measurements of equation (3). This is a well-known problem and has been solved by several authors using different techniques. Barnes obtained the steady-state solution using the ARIMA approach [7] and Tryon and Jones [4] obtained a dynamic solution including the effects of startup and variable δ .

The clock difference state estimator provides an optimal division of the observed time variations between the three noise sources based on the model. The time-scale problem is to assign the noise appropriately between the individual clocks based on the clock difference estimates. There are N clock noises for each of the phase, frequency, and aging states. However, there are only $N-1$ independent estimates of the clock difference noises for each state. Thus there are an infinite number of solutions that are consistent with the observations. A solution can be selected by removing the ambiguities with arbitrary but carefully selected restrictions. KAS-2 is defined by three equations

$$\begin{aligned} \sum_{i=1}^N a_i(t_k) \hat{\varepsilon}_i(t_k) &= 0 \\ \sum_{i=1}^N b_i(t_k) \hat{\eta}_i(t_k) &= 0, \\ \sum_{i=1}^N c_i(t_k) \hat{\alpha}_i(t_k) &= 0 \end{aligned} \quad (5)$$

where the weights for each of the states are positive semi-definite and sum to 1[1]. There remains the question of how to select the clock weights a_i , b_i , and c_i . Simulation and Monte-Carlo analysis have been used to show that when the weights are set inversely proportional to the variances of the random walk noises, the resulting time scale is generally better than all of the clocks in the short, intermediate, and long term [3]. Simulation also shows that the Allan variances of the estimated clocks are unbiased estimates of the Allan variances of the simulated clocks, *i.e.* the model. It is not known whether there are other solutions, based on different constraint equations, that share comparable good properties to KAS-2.

3.2. Robustness Algorithms

The Symmetricom Time-Scale System utilizes multiple levels of fault detection in order to provide a very high level of robustness. The first level is clock monitoring. Any fault generated by a clock is reported to the alarm sub-system and provides the operator with an opportunity to remove the clock from the time scale. The time scale computation itself provides two more levels of fault detection. An ARIMA pre-filter is used to analyze the clock difference data and detect inconsistent measurements. Outliers detected this way are reported to the time-scale algorithm and used to make decisions on whether to rely on the measurements. The pre-filter is used because the time scale is computed every 5 minutes but measurements are available every second. Thus, the pre-filter can react much more quickly than the time-scale algorithm itself.

The final robustness check is performed by the Kalman difference state estimator. Each measurement is compared to its forecasted value. The difference between the

measurement and its forecasted value is known as the innovation. If the squared innovation exceeds a multiple of the covariance of the innovation, then the responsible clock is de-weighted gradually until the weights are reduced to zero. This approach satisfies Percival's requirement for a robust filtering algorithm that deviant behavior by a small percentage of the frequency standards in a time scale does not unduly influence the resulting time scale [8]. Abrupt clock rejection is a discontinuous process that does not satisfy the requirement for robustness and can result in all clocks being rejected from the time scale. Human intervention is normally required to recover from such an event.

3.3. Steering Algorithms

The time-scale system can be configured so that only the desired independent clocks are included in the clock difference-state estimation and the time-scale computation. The clocks are un-steered and the resulting free running time scale, which is designated TA(lab), is analogous to TAI.

A second (coordinated) time scale, called TC(lab) is created by steering its frequency relative to TA(lab). The algorithm starts with estimating the phase and frequency offsets of TC(lab) from UTC. The phase offset in units of time is called x_{TC-UTC} , while the dimensionless frequency offset is designated y_{TC-UTC} . The steering algorithm corrects the full frequency error and a fraction of the phase error at each steer time by changing the frequency of TC(lab). Thus, the steering correction is given by

$$y_{steer} = -y_{TC-UTC} - G_x \frac{x_{TC-UTC}}{\delta}, \quad (6)$$

where G_x is the fraction of the phase error corrected in one steering interval, δ . A discussion of this type of optimal linear stochastic control by separating the process into two parts: state estimation and feedback appears in Gelb's book on optimal estimation [9].

TC(lab) can be steered to UTC automatically using data from the local GNSS receiver employing a combination of GPS and GLONASS satellites (or GPS only if desired). This is shown in Figure 4. TC(lab) can also be steered manually. One way of accomplishing manual steering is possible for a national laboratory that contributes clock data

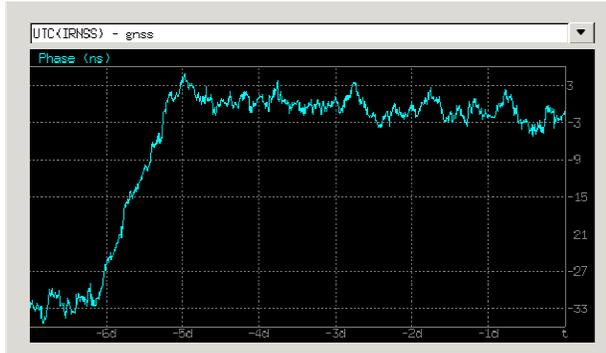


Figure 4: Automatic steering to GPS+GLONASS with 1 day time constant and 1 day interval.

to the UTC computation. The time-scale system always constructs the BIPM clock and GNSS reports. A participating laboratory can submit these reports and then enter the laboratory's offset from UTC that is published in Circular-T each month. The system's Web user interface has a function for entry of the (date, UTC offset) pairs and the system uses the built in steering algorithm of equation (6). The user sets the phase gain G_x and the steering interval.

A participating laboratory can also connect a SATRE modem to the time-scale system, which then computes the ITU format two-way report. Submission of this report to BIPM also results in the laboratory's offset from UTC being published in Circular-T and makes it possible to steer TC(lab) to UTC. Finally, any other source of UTC offset data can be used as a source of (date, UTC offset) pairs for manual steering.

For a participating laboratory, the frequency correction is applied every 5 days on modified Julian dates ending in 1.5 and 6.5 (half way between UTC computation dates). Each month, frequency and phase offsets are computed using a least square fit to the UTC offset data in order to get the state estimates required by the state variable control technique. The frequency offset is averaged with a user defined number of prior measurements and the averaged value is used to steer out the frequency offset of TC(lab) relative to UTC. The phase offset is steered out over a user defined time period by adding a phase correction steer to the frequency correction. Figure 5 demonstrates a manual steering test of a 1 μ s step with no frequency offset. The time constant was 1 hour and the update interval was also 1 hour. Since the time constant and the update interval are equal, the entire correction is made in the first update interval and the phase portion of the frequency steer is immediately set to zero, returning the coordinated time scale to its original frequency.

The final steering loop controls the output of the synthesizer in the real-time clock chassis to maintain the 5-MHz and 1-PPS signals on time with TC(lab). This loop utilizes the same state variable approach as the TC(lab) steering loop, but has a short time constant of 20 minutes so that it maintains its output within picoseconds of TC(lab). The physical output of the real-time clock is

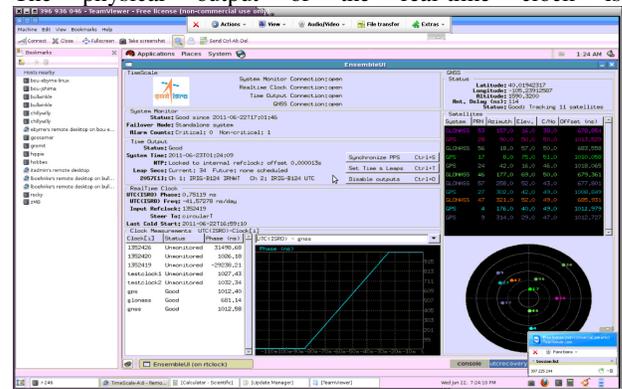


Figure 5: A manual steer of 1 μ s with a 1 hour time constant and 1 hour interval

designated UTC(lab). It is the official time-scale output and it is used to report all results to the BIPM.

4. PERFORMANCE

4.1. Stability

A time scale provides two fundamental features – continuity of time even in the event of clock failures and performance enhancements compared to a single clock. Figure 6 shows the real-time clock performance enhancement obtained in a six clock time scale comprised of five high-performance cesium clocks and one standard performance cesium clock. The steered clock, which is UTC(lab) has the performance of its reference clock at short times, but it has the performance of the free running time scale at long times. The time constant for steering the physical output to the time scale was 20 minutes. There is a very slight degradation of performance for times shorter than the time constant due to the steering and then the performance improves until it reaches the time-scale stability. The analysis was performed using the M-corner hat method of Jim Barnes [10].

The analysis was performed as follows:

Let $M \geq 3$ be the number of clocks

Let $\hat{\sigma}_{ij}$ be the estimate of the Allan deviation between clocks i and j

Let $\hat{\sigma}_i$ be the estimate of the Allan deviation of clock i (7)

$$\text{Define } B = \frac{1}{2(M-1)} \sum_{k=1}^M \left[\sum_{j=1}^M \hat{\sigma}_{kj}^2 \right]$$

$$\text{Then } \hat{\sigma}_i^2 = \frac{1}{(M-2)} \left[\sum_{j=1}^M \hat{\sigma}_{ij}^2 - B \right]$$

The clocks used in the analysis were the five un-steered cesium clocks and the UTC(lab) signal generated by steering a synthesizer whose reference clock is the sixth member of the ensemble. The analysis is valid in the case where the clocks are uncorrelated. However, since UTC(lab) is steered to the free running time scale, it is partially correlated with each of the other ensemble

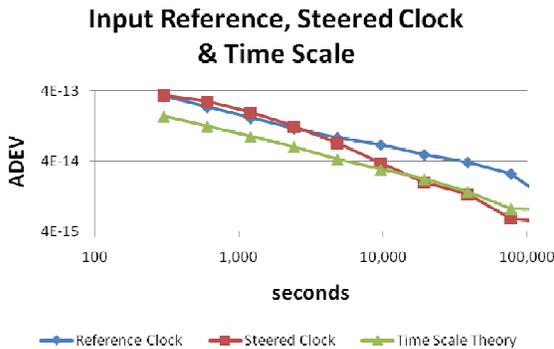


Figure 6: Performance improvement achieved by steering UTC(lab) to a computed time scale with 6 cesium clocks

members. Despite this correlation, the result is reasonable and the bias is small as demonstrated by the agreement with theory.

Additional stability data were obtained from a time scale whose ensemble comprised three high-performance cesium clocks and three active hydrogen masers. The analysis was performed using the traditional 3-corner hat method, which is given by equation (7) when $M=3$. The result is shown in Figure 7. Once again it is seen that the UTC(lab) output has better stability than either of two of the masers. The results of the three-corner hat analysis are biased since the UTC(lab) output is highly correlated with the other two masers in the time scale due to the steering. The bias was estimated by performing 3-corner hat analysis of the three free running masers and observing the difference in the stability obtained this way with the stability obtained when one of the masers is replaced by the steered clock. The estimated size of the bias is 0.5 and has been removed to show the unbiased performance of the time scale, which is 1×10^{-15} at one day.

4.2. Accuracy

The calibrated time-scale accuracy is 10 ns 1σ . After calibration, a test was run to determine the accuracy of the time-scale system vs. UTC. The result is shown in Figure 8.

5. CONCLUSIONS

A time scale is nothing more than a method of estimating the individual time of a clock that is a member of an ensemble of several clocks. The problem is under-defined because only clock time-difference measurements are available. The approach presented in this paper removes the ambiguity by forcing the finite ensemble of clocks to have a property that is true in the limit of an infinite number of clocks – the weighted sum of the random noise inputs to the clocks is zero. The result is an algorithm whose performance may be optimized in each region where a different noise type is dominant.

A turn-key system that implements a practical time scale has been described. This system achieves all the requirements of a national time scale – an independent free running time scale, a coordinated time scale that may be

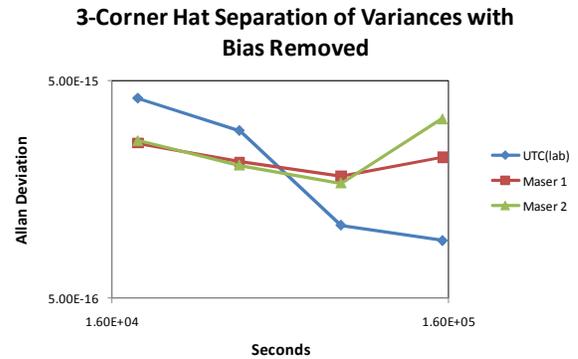


Figure 7: Short-term stability of a time scale with 3 active H masers and 3 high-performance Cs clocks

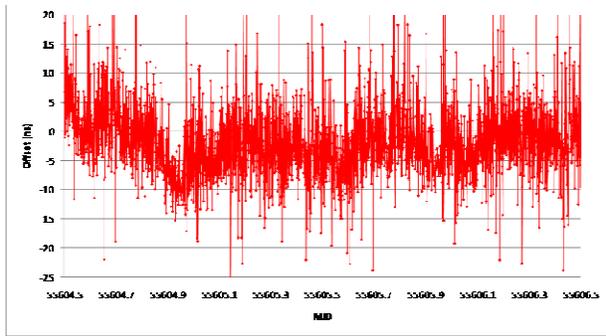


Figure 8: Time Scale accuracy test after common-view calibration of the GPS receiver.

steered to UTC, and a physical output steered to the coordinated time scale that may be used as a national UTC(lab) signal. Results have been presented showing that this fully automated system achieves the theoretically expected performance.

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