WORKING APPLICATION OF TWSTT FOR HIGH PRECISION REMOTE SYNCHRONIZATION

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Abstract

Two-way satellite time transfer (TWSTT) is the primary method implemented to determine the synchronization error between the United States Naval Observatory (USNO) Alternate Master Clock (AMC) located in Colorado and the USNO Master Clock located in Washington, DC. A hydrogen maser at the AMC is controlled to the USNO Master Clock within 1 ns RMS as determined by low noise (< 300 ps) TWSTT measurements. A Kalman filter utilizes the TWSTT time difference data to give real time synchronization and syntonization error estimates that are used in a linear quadratic Gaussian control design. Calibration runs using a mobile earth station monitor the long term performance of the TWSTT method. Results of a closed loop TWSTT calibration experiment will be discussed.

Introduction

In this paper we describe how two-way satellite time transfer (TWSTT) is utilized in the remote realization of the United States Naval Observatory (USNO) Master Clock at the USNO Alternate Master Clock facility (AMC). The USNO Master Clock is located in Washington, DC and the AMC is located in Colorado. A Kalman filter utilizes the TWSTT time difference data to give real time synchronization and syntonization error estimates that are used in a linear quadratic Gaussian control design.

The first section gives an overview of the AMC purpose along with a description of the system. The next section briefly covers the TWSTT method followed by a summary of the AMC TWSTT link. Stochastic control of frequency standards is the topic of the following section. Data are then given on the performance of the AMC system.

USNO Alternate Master Clock (AMC)

The AMC is located at Falcon Air Force Base near Colorado Springs, CO. The AMC serves as a backup facility for the USNO Master Clock system and can take over the highest priority tasks conducted at the USNO facility in Washington, DC should the need arise [4]. The AMC also acts as a precision remote realization of the USNO Master Clock. The AMC Master Clock signal is used as a frequency standard at the GPS monitor station at Falcon AFB.

The AMC is a state of the art facility with a system that is comprised of 2 atomic hydrogen masers, 14 cesium standards, several GPS receivers, 4 environmental chambers, and 10 racks of precise timing equipment.

Two-way Satellite Time Transfer (TWSTT)

TWSTT is the most precise method being utilized for disseminating time at the present ([8],[9]). It has the capability of performing time transfer with a precision on the order of 300 picoseconds. One of the great advantages of TWSTT is the fact that atmospheric and other potential perturbations are seen simultaneously in each path and therefore cancel to a high degree during the measurement cycles. This technique has been in use since 1962 when the precision was at the 0.1 to 20 microsecond level [8].

TWSTT measurements are accomplished by both participating laboratories measuring the time interval difference between the local reference standard 1 pulse per second (PPS) and that which is being received via the satellite link using a spread spectrum technique [6]. If all the path delays are reciprocal, that is that the delay from station 1 to station 2 is same as the delay from station 2 to station 1, the time difference between the two laboratories is the time difference measured by the modems. Due to non-reciprocal time delays in the system, reciprocity cannot be assumed. The time difference between the stations is given as

$$
\begin{aligned}
T_1 - T_2 = {} & \frac{1}{2}(\Delta T_1 - \Delta T_2) \\
& + \frac{1}{2}[(\tau_1^U + \tau_2^D) - (\tau_2^U + \tau_1^D)] \\
& + \frac{1}{2}(\tau_{12} - \tau_{21}) \\
& + \Delta\tau_R \\
& + \frac{1}{2}[(\tau_1^{Tx} - \tau_1^{Rx}) - (\tau_2^{Tx} - \tau_2^{Rx})].
\end{aligned}
$$

The first term corresponds to the time difference measured at each station. The second term pertains to the signal delays from the up and down satellite links. The satellite transponder delays make up the third term. $\Delta\tau_R$ is due to the relativistic Sagnac effect. The last term corresponds to the delays in transmitting and receiving at each of the stations [9].

A calibration run using a mobile earth station or portable fly-away dish with known properties and delays is necessary to calibrate the total system [15]. The AMC was calibrated during the initial system setup. A follow up calibration approximately one year later was within 300 ps of the original measurement.

AMC TWSTT Link

The TWSTT link between USNO and AMC is shown in block diagram form in Fig. 1. The USNO Master Clock provides the reference 5 MHz and 1 pulse per second signals that are required for the TWSTT modem at USNO. A commercial satellite operating in the Ku band is used for AMC TWSTT link. An attempt is made every hour to measure the synchronization error between the AMC and the USNO Master Clock. The historical success rate of obtaining a measurement is approximately 80%, with most of the failures occurring due to older generation modems not properly locking. New modems that are planned to be installed should increase the success rate.

After the time difference data have been analyzed at USNO, a computer at AMC collects the data via the Internet or by other means such as dial up modems should the Internet connection fail. The measured data point is then used as the input for a Kalman filter estimate calculation. This Kalman estimate is used in conjunction with a linear quadratic Gaussian (LQG) calculated gain to produced the necessary frequency steer to be applied to the AMC Master Clock.

An Auxiliary Output Generator (AOG) frequency synthesizer is used to give the frequency steer a physical realization. A hydrogen maser 5 MHz signal is the reference input into the AOG. The frequency steers adjust the maser reference input signal so that it is synchronized to the USNO Master clock as determined by the TWSTT measurements. The output of the AOG provides the reference 5 MHz and 1 pulse per second signals that are required for the TWSTT modem at AMC.

Stochastic Control of Frequency Standards

Noisy measurements combined with stochastic noise inherent in processes make real time parameter estimation both difficult and interesting. In the AMC system the disturbances come in the form of the TWSTT measurement system noise and the random characteristics of the frequency standards being compared. Kalman filtering ([1],[2],[3],[13], and [14]) is used to estimate the AMC offsets in time and frequency with respect to the USNO Master Clock. In Kalman filter theory the state equation is assumed to be given as a linear function of a state vector, **x**(k), a control vector, **u**(k), and a noise vector **w**(k):

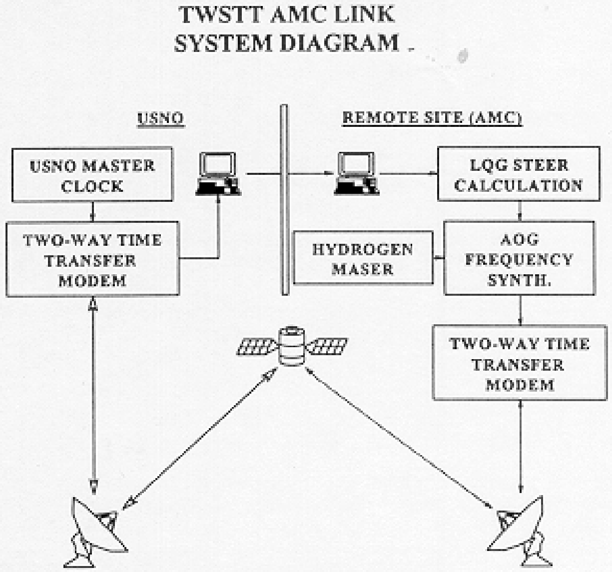

Fig. 1. AMC TWSTT link block diagram

$$x(k+1) = \Phi x(k) + Bu(k) + w(k),$$

where for the two state frequency standard model,

$$\Phi = \text{transition matrix} = \begin{bmatrix} 1 & \tau \\ 0 & 1 \end{bmatrix}, \tau \quad \text{is the time interval}$$

between measurements,

$$x(k) = \text{state vector} = \begin{bmatrix} x_1(k) \\ y_2(k) \end{bmatrix},$$

$x_1(k)$ is the time difference, and $y_2(k)$ is the fractional frequency difference, between the reference and the steered standard,

$$\mathbf{B} = \begin{bmatrix} \tau \\ 1 \end{bmatrix},$$

$u(k)$ = control vector which is a scalar corresponding to the fractional frequency change of the synthesizer controlling the steered standard,

$w(k)$ = Gaussian white process noise

The noisy measurement $z(k)$ is related to the state vector

$$z(k) = Hx(k) + v(k)$$

where

$z(k)$ = measurement, in our case a scalar time difference,

H = connection matrix = [1 0], and

$v(k)$ = Gaussian white measurement noise.

After the state comprised of the phase and frequency offsets has been estimated, the data are used with an LQG calculated control gain in order to produce a frequency steer value. The LQG method ([2],[3],[5],[7],[10] and [12]) calculates a gain such that the cost function

$$J = E[\sum_k [\hat{x}(k)^T W_Q \hat{x}(k) + u(k)^T W_R u(k)]]$$

is minimized.

W_Q and W_R are matrices that are chosen in order to set the relative penalties assessed to the state vector estimate $\hat{x}(k)$ and control vector $u(k)$ as they vary from zero. The optimal control for the given cost function is given by the linear equation

$$u(k) = -\hat{G}_0 \hat{x}(k),$$

where $\hat{G}_0$ is calculated by solving a Ricatti equation.

AMC Performance Data

The AMC has been synchronized to the USNO Master Clock within 700 ps RMS as given by TWSTT data over approximately a two year period. A Kalman filter is used to estimate the time and frequency offsets between AMC and the USNO Master Clock. The Kalman filter calculates an optimal estimate based on given process and measurement system noise parameters. The real time Kalman estimates of the data are also plotted in Fig. 2.

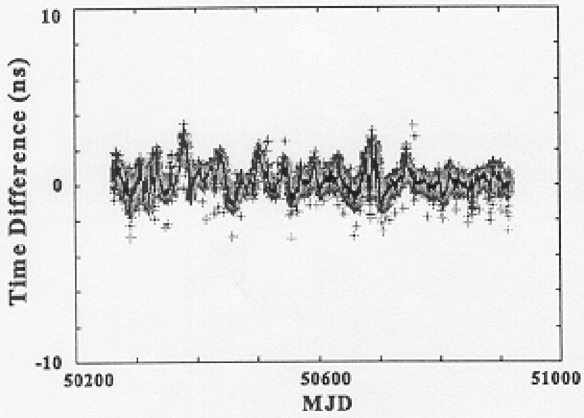

Fig. 2. Time difference between USNO Master Clock and AMC via TWSTT. Dashed crosses are the measured data and the black line is the real time Kalman estimate.

A one step ahead prediction is made from the time and frequency estimates as given by the Kalman filter. The difference between this estimate and the corresponding measurement is referred to as the innovation. More formally the definition of the innovation , $\nu(t)$, is

$$\nu(t) = Z(t) - E\{Z(t)|Z(1)Z(2) \ldots Z(t-\tau)\},$$

where the second term reads the expectation of the noisy measurement Z(t) given all the data up to and including the previous measurement of Z. Fig. 3 is a plot of the Kalman filter innovations of the data measured at AMC. The innovations are dominated by the noise of the TWSTT link.

The innovations are utilized as a real time outlier detector. In the present design all measurements that cause the innovation to be larger than +/- 3 ns are thrown away. It appears that the filter could be tightened up to +/- 1 ns. It is interesting to note that most of the outlying points tend to be in the negative sense. The reason for this is unknown at present.

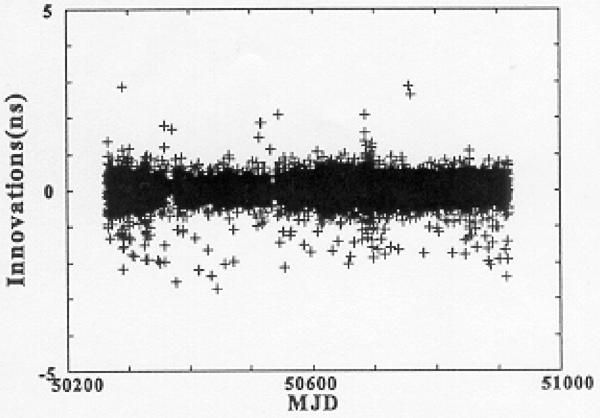

Fig. 3 Innovations of the measured data given in Fig. 2.

Frequency steers are calculated using the Kalman estimates of the time and frequency offsets along with a linear quadratic Gaussian calculated control gain. A gain has been chosen so that the time and frequency offsets and the frequency perturbations due to the steers are all within acceptable performance parameters. This determination was

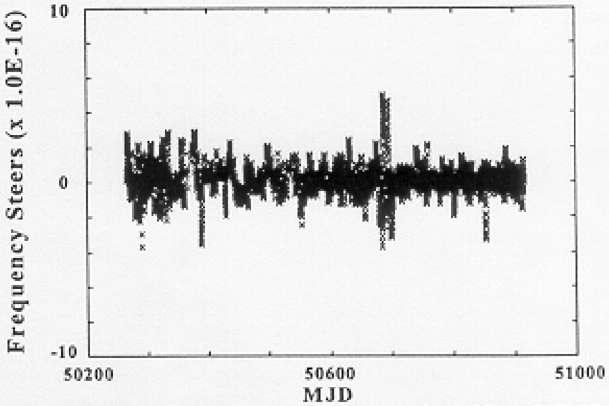

Fig. 4. Frequency steers used to control AMC to USNO Master Clock.

made possible by steering simulations that were conducted on real archived data. A plot of the frequency steers needed to control the AMC Master Clock to the USNO Master Clock is given in Fig. 4.

A plot of the frequency offset generated by the AOG over approximately a year is given in Fig. 5. The reference for the AOG is Sigma Tau hydrogen maser N13. The plot shows the short term variations caused by the steering and also the relative drift of less than $1.0*10^{-16}$ per day between N13 and the AMC Master Clock.

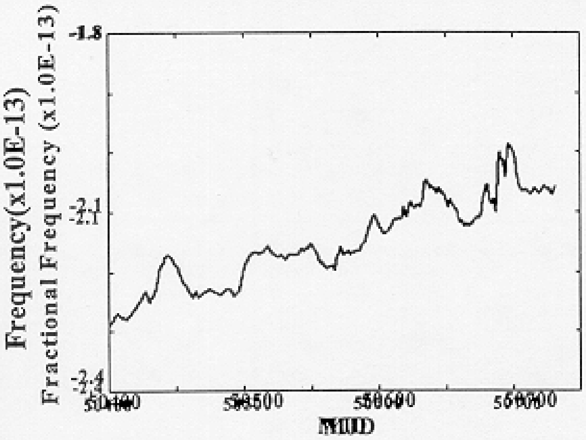

Fig. 5 Relative frequency of the input vs. output of the frequency synthesizer. Reference is hydrogen maser N13.

The frequency stability performance of the AMC Master Clock along with the time and frequency errors with respect to USNO Master Clock are the main parameters of concern. The frequency stability perturbation of the N13 maser output caused by controlling it to the USNO Master Clock is shown in Fig. 6. The Allan deviation of the AMC Master Clock remained below $2.0*10^{-15}$ for averaging times from 1 hr to 42 days with respect to the free running maser N14. The disturbance at 10^{6} second averaging time was predicted by simulation [10].

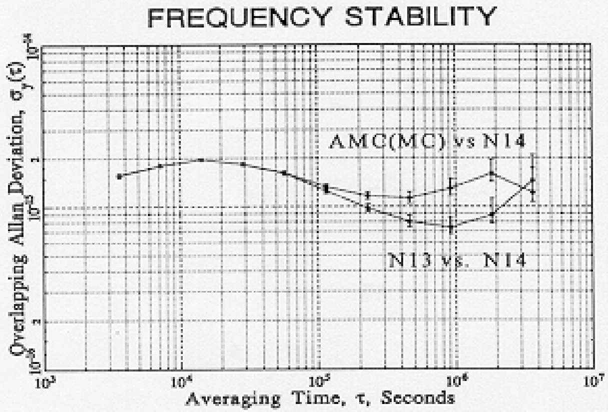

Fig. 6. Allan deviation of AMC Master Clock vs. hydrogen maser N14 and masers N13 vs. N14

Calibration Testing

Fig. 7 shows a block diagram of an experiment ongoing at USNO in Washington, DC. The test utilizes a common reference, the USNO Master Clock, and two satellite dishes located near each other at USNO. By using the common reference and having independent communications systems, the characteristics of the noise due to the TWSTT method may be studied. Monitoring any bias or calibration change over the long term is of particular interest. Fig. 8 gives initial test results of the experiment.

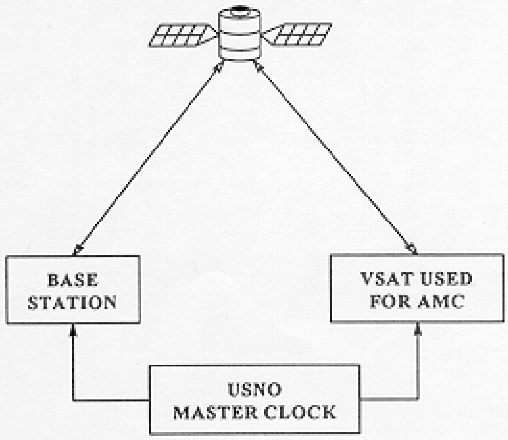

Fig. 7. Calibration monitoring experiment at USNO.

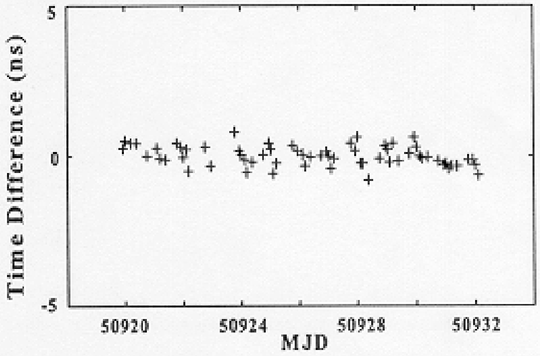

Fig. 8. Initial calibration test data.

Conclusion

TWSTT is being utilized to remotely control the AMC Master Clock in Colorado to within 1 ns RMS of the USNO Master Clock located in Washington, DC. The parameters of the control system where chosen so that the AMC Master Clock would exhibit excellent frequency stability characteristics while being steered to be on time and frequency to the USNO Master Clock. Tests to characterize TWSTT calibrations are ongoing.

References

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