Simulation Study for Commercial Time Transfer Service over Geostationary Satellite

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Abstract—Over the last twenty years, many technologies and services have come to rely on the GPS for precise timing. Concern is increasing about the wisdom of being reliant on a single timing solution provided by a single country and because of the susceptibility of the GPS signal to unintentional interference, jamming and spoofing. In this paper, we report on further development of our system for timing signal transfer from a precision reference clock using commercial satellite links. The system will have a set of master stations tracking the satellite position and using TWSTFT measurements to synchronize their clocks, transmitting data with the reference timing signal to allow slave stations to adjust the PPS timing signal, compensating for the satellite motion and other uncertainties in the path delay. We will report on a simulation of the full system, including models for the master station clocks and TWTT measurements, using a Kalman filter to track the satellite position.

Keywords—time transfer; satellite; TWSTFT; TWTT; timing; synchronization

I. INTRODUCTION

Over the last twenty years, many technologies and services have come to rely on the GPS for precise timing. However, concern is increasing about the wisdom of being reliant on a single timing solution [1] provided by a single country because of the susceptibility of the GPS signal to unintentional interference, jamming and spoofing [2]. There are several projects underway to develop similar systems or upgrade existing ones, e.g. Galileo, GLONASS. Only one of these systems (GLONASS) is currently fully available as an alternative, with the other systems projected to become operational progressively during the next decade. In the current situation, if the quality of the GPS signal deteriorates, some of the main information and communications channels would not be usable in many countries, causing a wide range of problems [1], [2]. Other approaches to timing transfer exist and are being developed: over optical media [3] or using high power LF signals [4] and over satellite links [5],[6],[7],[8]. Timing transfer over optical media shows promising performance but requires the installation of a dedicated network infrastructure. High power, low frequency radio signals are an established solution but cannot easily cover such a wide geographical area as a satellite solution.

In this paper, we report on further development of our system for timing signal transfer from a precision reference clock using commercial geostationary satellite links [7],[8]. The system will have a set of master stations tracking the satellite position and using TWSTFT measurements to synchronize their clocks. Data transmitted with the reference timing signal will allow slave stations to adjust the timing signal, compensating for the satellite motion and other uncertainties in the path delay. Using projected ephemeris data and comparing that data in real time with measurements, which themselves are affected by other sources of delay, is a challenging task when the goal is timing signal transfer with no more than 100 ns of jitter peak-to-peak at the receiving stations and motivates study of the system using simulations. The paper is structured as follows: in Section II, we briefly review the structure of the time transfer system and previous experimental and simulation findings. In Section III, a new simulation of the system is presented. Results from the simulations are presented in Section IV. Finally, in Section V we present our conclusions.

II. ONE-WAY SATELLITE TIME TRANSFER SYSTEM

The time transfer system under development by Mixed Processing Ltd and University of Limerick researchers will provide a complete off-the-shelf system for precision time transfer over geostationary satellite. The full system will consist of three master stations to fix the satellite position. The master stations communicate with each other and with the receive-only slave stations using bandwidth rented from a commercial satellite provider. One master station will have a high precision clock such as a Cesium atomic clock and two sub-master stations will have precision clocks with a high holdover capability e.g. Rubidium clocks. Each of the master stations, whether master or sub-master, will have a bi-directional link to the satellite. Finally, there are slave or receive-only stations which have a uni-directional (receive) link with the satellite. The slave stations will be sent a pulse-per-second (PPS) time signal and data that allows them to compensate for the timing uncertainty arising from the satellite motion and other sources. The master stations will exchange satellite ranging data to track the satellite position and align their clocks using TWSTFT. In order to determine accurately the propagation time of signals between the master station and the slave stations it will be necessary to consider and correct
for errors in the path delay determination arising from: satellite ephemeris errors, satellite motion, atmospheric effects, temperature induced delay variation in cables and outdoor equipment, the Sagnac effect and general measurement errors.

A. Proof of Concept Experiment and Simulations

A previous proof of concept experiment was successfully conducted with a single master station broadcasting a PPS timing signal to three slave stations with an accuracy of at worst 1 µs when compared to a GPS PPS reference, was reported on in detail in [7],[8]. In a three master station system, the stations measure their own range to the satellite and the three measurements may be used to calculate the satellite position by trilateration. However, the range measurements contain extraneous delays, not all of which can be known exactly, e.g. the delay through the satellite transponder or the exact value of the atmospheric delay. Furthermore, with three master stations, each with their own independent clock, two of the measurements contain an error with respect to the measurement taken by the primary master station, due to the clock difference between stations. One approach is to measure and estimate the extraneous delays as accurately as possible. Clearly equipment and cabling delays at each station can be measured while an estimate for the troposhere delay can be predicted using an atmospheric model [9]. At the Ku-band transmission frequencies, the effect of the ionosphere can be neglected [10]. Then, using the satellite ephemeris, the master stations can find a correction factor to account for the remaining unknown and variable extraneous delay. The primary master station calculates the satellite position using trilateration, using two-way time and frequency transfer to correct for the clock phase difference. However, a simulation of this approach demonstrated the sensitivity of the satellite position calculation to unknown variation in the extraneous delays [7].

III. AN APPROACH USING A KALMAN FILTER

To test an alternative approach, a simulation for a three station system where the primary master station uses an extended Kalman filter to predict the satellite position, thus integrating its own measurements with those of the other two master stations, has been developed.

As is well known [11], a discrete-time Kalman filter uses a two stage procedure to first predict the next state $x_k$ of a discrete-time system which may be described by a linear stochastic difference equation,

$$\dot{x}_k = A x_{k-1} + B u_{k-1} + w_k$$

where $A$ is the state transition matrix, $u_{k-1}$ is an optional control input, $B$ is an optional control matrix and $w_k$ is an independent white noise process. A measurement $z_k$, which is related to the state of the system by a linear measurement matrix $H$ as:

$$z_k = H x_k + v_k$$

where $v_k$ is an independent white noise process, must also be available. In a linear discrete-time Kalman filter, where there is no control input, the next state of the process is estimated using:

$$\hat{x}_k = A \hat{x}_{k-1}$$
$$P_k^- = AP_{k-1}A^T + Q$$

where $\hat{x}_{k-1}$ is the a priori state estimate, $\hat{x}_k^-$ is the a priori state estimate, $P_k$ is the estimate error covariance matrix, where the superscript minus denotes the a priori estimate, and $Q$ is the process noise covariance matrix, which is used to include an estimate of our uncertain knowledge of the underlying process [12]. In the second stage of the Kalman filter, the Kalman gain matrix, $K_k$, is used updating the measurement matrix $H$, the a priori estimate error covariance $P_k^-$ matrix and $R$ the measurement noise covariance matrix. The noisy measurement is compared with the predicted measurement made using the a priori state estimate, and the error, adjusted by the Kalman gain is used to update the state prediction to produce the a posteriori state estimate and the updated error estimate covariance predictions.

$$K_k = P_k^- H^T (H P_k^- H^T + R)^{-1}$$
$$\hat{x}_k = \hat{x}_k^- + K_k (z_k - H \hat{x}_k^-)$$
$$P_k = (I - K_k H) P_k^-$$

A. Kalman Filter System Model

The Kalman filter approach used for the simulation was originally developed based on that described in [13], where a Kalman filter was used to track the position of a geostationary satellite using GPS satellites. In [13], the satellite path is described by the simple circular motion continuous-time dynamics model:

$$\dot{x} = F x$$

where the first three rows of $x = [X \ Y \ Z \ \dot{X} \ \dot{Y} \ \dot{Z}]^T$ are the position vector of the satellite, the bottom three rows are its velocity vector, and the dynamics matrix $F$:

$$F = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ -\mu/r^3 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\mu/r^3 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\mu/r^3 & 0 & 0 & 0 \end{bmatrix}$$

where $\mu = 398600.4418 \pm 0.0008$ km$^3$/s$^2$ is the gravitational constant and $r=\sqrt{X^2 + Y^2 + Z^2}$. In the simulation reported upon here,
as the equations of motion are non-linear, a linearized system dynamics matrix is used to develop the Kalman filter equations

$$\Delta\dot{x} = dF\Delta x$$ \hspace{1cm} (6)

where $dF$ is the Jacobian of the continuous-time dynamics matrix. The linearized continuous-time dynamics matrix is then discretized to produce the discrete-time state transition matrix using a first-order approximation [12].

In [13], the simulation used ECI (Earth-Centred Inertial) co-ordinates and the results were converted to the ECEF (Earth-Centred Earth Fixed) system for analysis and display. The ECI frame has its origin fixed at the centre of the earth and may be considered a fixed frame of reference (neglecting the much longer period motions of the earth in space [14]) so that the equations of motion of the satellite are simpler to express in this frame. However, as the ground truth for the simulation will be satellite ephemeris data in ECEF co-ordinates, the system dynamics matrix was transformed into that co-ordinate system. Another reason for formulating the satellite motion model in the ECEF frame is that the earth rotates with respect to the ECI frame and it requires finding the position of the vernal equinox at a particular time [15]. Such a requirement is to be avoided in an application whose purpose is to transfer a precise and accurate determination of time, as it will add additional uncertainty to the path tracking. Hence, the system dynamics matrix was converted into its equivalent in ECEF co-ordinates.

The measurements available to the Kalman filter are the range measurements between each master station and the satellite position given by:

$$\rho = \sqrt{(x - x_m)^2 + (y - y_m)^2 + (z - z_m)^2}$$ \hspace{1cm} (7)

where $(x, y, z)$ is the satellite position at the given time instant and $(x_m, y_m, z_m)$ is the position of the ith master station. Since these measurements are nonlinear, an Extended Kalman filter is used where the measurement matrix is replaced by the observational partial derivative matrix [13].

An important aspect of the system is that the clocks in the master stations, being independent and geographically separated, will not be synchronous. In the present simulation, the error due to the difference between the clocks and two-way time transfer (TWTT) is easily incorporated by using a discrete-time random process to model the bias, drift and drift rate in the clocks at each master station in a similar approach to that used in [13]. Using the clock bias output of the clock model (in seconds) and multiplying the difference between two clocks’ bias by the speed of light $c$ the resulting measurement error due to the phase difference may be modeled by in meters and added to the measurements.

$$\rho_k = \sqrt{(x - x_m)^2 + (y - y_m)^2 + (z - z_m)^2} + cb_m - cb_m + v_k$$ \hspace{1cm} (8)

where $b_m$ is the bias on the ith master station clock and $v_k$ is the measurement noise. The two-way time transfer measurement between the primary master clock and the ith clock at the ith master station can be modelled as [13]:

$$\Delta T_{ij} = cb_{mi} - cb_{mj} + v_{ij}$$ \hspace{1cm} (9)

where $v_{ij}$ is the error in the TWTT measurement.

B. Kalman Filter Simulation Procedure

The simulation uses as ground truth archived satellite path data for E33A from November 2010 as was used in the original experiment [7] interpolated to provide the ground truth satellite path. Given the master station positions, the measurements to be used by the simulation can then be created offline using equation (8). In the simulation the procedure assumed is that communication between the master stations permits the primary master station to collate the range measurements from the two other stations as well as the phase difference between its own clock and those of the other two master stations. The Kalman filter for tracking the satellite position is then run at the primary master station. The primary master station will send the PPS timing signal to the slave stations with the estimated satellite position and its own range to the satellite. At the slave station, the slave uses the satellite position to calculate its own range to the satellite and it can then calculate the expected time of arrival of the PPS signal. To measure the performance of the simulation, the expected time of arrival is compared with the simulated real travel time of the signal to determine the residual time variation on the received PPS signal after adjustment in a procedure which simulates that in the original experiment [7], [8].

IV. RESULTS

To verify the tracking capability of the Kalman filter, it was run without perturbations, apart from the satellite motion. The standard deviation of the tracking error, the difference between the ground truth satellite co-ordinates and the filter’s estimate is 0.3m to 0.6m and the standard deviation of the adjusted PPS signal at the slave is 2ns. To make the simulation more realistic, perturbations are then added back to the simulation. Fixed extraneous delay quantities such as equipment delay, mean troposphere delay or the Sagnac effect are not included as within a simulation it is pointless to add them in and then subtract them again. Instead, the approach is to use normally distributed noise to simulate the variable and unknown part of the extraneous delays. Thus, a variable component to represent the unknown and varying atmospheric delays is added to the time of travel of the PPS sent from primary master to slave station. This quantity is also added to the range measurements. As shown in (8), the clock phase differences are added to the range measurements along with a measurement noise which represents all the other uncertainties such as those to do with the resolution and noise within the transmitter and receiver systems.
Examples of typical simulated tracking and time transfer results obtained so far from the simulation are shown in Fig. 1 and Fig. 2. The standard deviation of the measurement noise was 15m, the variable component of the delay due to atmosphere was typically < 10m and the effect of noise on the TWTT measurements was modeled as < 1m. The measurement residual with these settings was typically 10-50m, resulting in a tracking error standard deviation of 200-400m. The simulated time transfer performance was within ±150 ns as shown in Fig. 2.

V. CONCLUSION

In this paper we have described the proposal by Mixed Processing Ltd for an off-the-shelf system for timing signal transfer over geostationary satellite. The proposal for the full system with three master stations tracking the satellite position and broadcasting a timing signal to slave stations has now been simulated implementing a Kalman filter approach to the satellite tracking with some encouraging preliminary results. The simulation will now be used to explore the effect of variable extraneous delays on tracking and time transfer performance.

REFERENCES


