Clock Synchronization Protocol for Distributed Satellite Networks

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Abstract- **Several future space missions are being planned with large number of spacecrafts at Low Earth Orbit (LEO) and beyond where clock synchronization using GPS will partly be impossible or insufficient. Onboard local clock synchronization devices will be required to replace or augment the available GPS measurements to keep the clocks of the spacecrafts synchronized at low cost. Clock synchronization is very important for many applications, e.g. bi/multi-static SAR systems require clock synchronization for the accurate interferometric phase evaluation. This paper presents a method to relatively synchronize the clocks in such distributed satellite networks when GPS is not available.**

I. INTRODUCTION

Individual nodes in a distributed sensor system, ranging from earth to deep-space applications, need to collaborate to accomplish a common task (e.g. data fusion). This can be done by exchanging messages that are time-stamped using the local clocks on the nodes. The shared notion of time is required to co-ordinate activity or to maintain the temporal order of results. Clock synchronization is therefore an indispensable piece of infrastructure for such systems. A link between two satellites can provide direct measurements of clock synchronism and inter-satellite range [1] that are more accurate than estimates obtainable from ground measurements. The relative estimated clock parameters obtained from the inter-satellite communication links might be cooperatively used for the clock error compensation when coherent signal processing is performed (e.g. the phases generated from the complex interferogram).

The clock error behavior has been observed in [2] through the analysis of a very long segment of ERS-1 data in which the fringe patterns show features which can be caused only by drift of internal clock. It becomes a new challenge to synchronize the clock of distributed satellites within a certain design tolerance. In practice, Global Positioning System (GPS) is used to keep the clocks of satellites synchronized. However, for certain scenarios in which the use of GPS is unfeasible, an alternative method shall be considered. This work focuses on synchronizing the clocks of the micro-satellites as a supplement to GPS system.

A. General Clock Definition

Nearly all computing machines have a circuit for keeping track of time. Despite the widespread use of the word “clock” to refer to these devices, they are not actually clocks in the usual sense. *Timer* might be a better word. An electronic timer is usually a precisely machined quartz crystal. When kept under tension, quartz crystals oscillate at a well-defined frequency that depends on the kind of crystal, how it is cut, and the amount of the tension. Associated with each crystal are two registers, a *counter* and a *holding register*. Each oscillation of the crystal decrements the counter by one. When the counter gets to zero, an interrupt is generated and the counter is reloaded from the holding register. In this way, it is possible to program a timer to generate an interrupt 60 times a second, or at any other desired frequency. Each interrupt is called one *clock tick*.

B. Terms in Clock Synchronization

In the paper describing the Network Time Protocol (NTP), Mills [3] defines the various terms used in clock synchronization. The *stability* of a clock is how well the physical clock can maintain a constant frequency. *Accuracy* refers to how well the maintained time is true to a standard time. The *offset* of two clocks is the actual time difference between them, and the *skew* is the frequency difference between them. To *synchronize frequency* means to adjust the clock to run at the same frequency. To *synchronize time* means to set their time at a particular epoch to be exactly the same. To *synchronize clock* means to synchronize the clocks in both frequency and time.

C. Sources of Synchronization Error

Non-deterministic delays in the radio message delivery in the distributed systems can be magnitudes larger than the required precision. Therefore, these delays need to be analyzed and compensated for. These delays are considered in [4] and shortly summarized here:

Send Time - Time at the transmitter used to construct the message and issue the send request to the MAC layer. Depending on the system call overhead of the operating system and on the current processor load.
Access Time - The delay associated with accessing the radio channel. This is specific to the MAC protocol in use.
Propagation Time - Time needed for message to travel from sender to receivers once it has left the sender. The propagation time is a function of the distance between the satellites.
Receive Time - The processing time required for the receiver to receive a message from the channel and notify the host of its arrival.

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This paper proposes an algorithm that has been initially introduced for wireless sensor networks (WSN) by J. Elson [5]. In future satellite missions, e.g. Cartwheel configurations, the system can also be considered as a network with higher nodes' capability as compared to common WSN. Therefore, one could possibly modify the existing algorithms in WSN for satellite networks.

II. CLOCK MODEL

An accurate (but not perfect) clock produces a pulse once per second (1 PPS). The times of these pulses are compared to those produced by a perfect reference (Cesium) clock. The error is given by the discrete-time signal y, where y_k denotes the time difference between the k^{th} pulse (k^{th} second) of the clock under consideration and the perfect reference clock. Therefore the error as compared to the perfect clock of many types of clock can be modeled [6] as

$$y_k = \alpha + \beta \cdot k + \gamma \cdot k^2 + n_k \tag{1}$$

where $\alpha \in \Re$ is the relative initial phase offset, $\beta \in \Re$ is the relative clock drift, $\gamma \in \Re$ is the relative rate of change in frequency or frequency drift, and $n_k \in \Re$ is called the clock jitter; it is random and unpredictable. The jitter is modeled as zero mean white Gaussian noise with standard deviation σ_n.

In the following chapters we will restrict ourselves to a simplified model in which the quadratic term in (1), often referred to as aging, is neglected. Clock offsets and skews of the local clocks are shown in Fig. 1. For the ideal case the line representing local clock must coincide with the perfect clock ($\alpha = 0$ and $\beta = 1$).

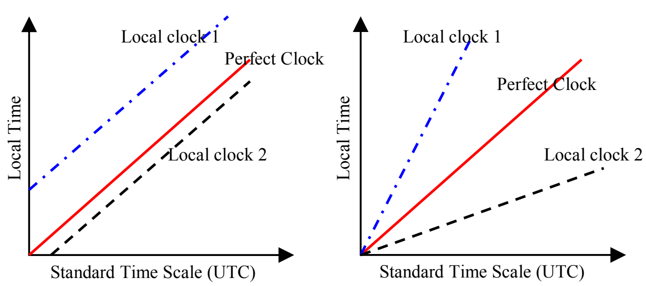

Fig. 1: Clock offset and skew as compared to the universal time standard

III. CLOCK SYNCHRONIZATION

The proposed technique takes advantage of inherent broadcast nature that removes two sources of synchronization errors (Send and Access Time) which are typically the biggest contributions to the non-deterministic latency. For relatively small networks, propagation time could be negligible in some cases since the algorithm is only sensitive to the difference in propagation time between a pair of receivers. However, for satellite networks, the uncompensated distance between the satellites in the range of 100m to 15km will lead to 333 nsec to 50 µsec synchronization error. Therefore, to obtain nsec accuracy, these distances have to be compensated for. We assume that the propagation delay can be roughly computed and compensated for. Moreover, all micro-satellites must be in the same broadcast domain of a single master satellite and inter-satellite communication channels among micro-satellites are required. The oscillators are also assumed to have high "short-term" frequency stability.

A reference pulse transmitted by the master satellite will be received by all micro-satellites in its broadcast domain and these receiving micro-satellites will time stamp the arrival of the reference pulse, as shown in Fig. 2. Using a series of receive-time differences between two micro-satellites, the proposed technique can accomplish curve fitting based on Kalman filtering and this is able to estimate clock skews and offsets relative to the other micro-satellites.

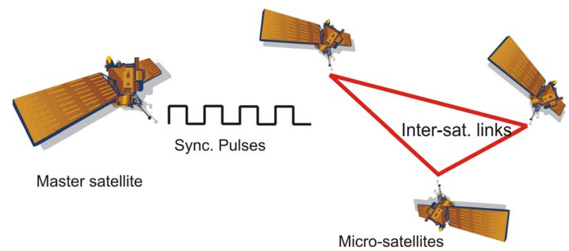

Fig. 2: Clock synchronization protocol applied to satellite network

The relative offsets and the skews of a local clock can be obtained by finding the best fit line $y = \alpha + \beta x$ through the phase error observations over time. For example, with two micro-satellites for each synchronization pulse k that is received by satellite *r1* and *r2*, we can plot $x_k = T_{r1,k}$ and $y_k = T_{r2,k} - T_{r1,k}$ where $T_{ri,k}$ is the r's clock when it received broadcast k. By applying a Kalman filter, the slope α and the line intercept β can be computed. The slope of the best fit line gives the relative clock skew, when measured by satellite r_1's clock. The line's intercept gives the relative initial phase offset. Thus, it is sufficient to convert any time value generated by r_1's clock to the value that would have been generated by r_2's clock at the same time. Furthermore, the initial phase offset and clock skew information between two micro-satellites might also be used to reduce distortions in the interferogram caused by phase offset and linear ramp error.

IV. PROBLEM FORMULATION

N micro-satellites exchange their recorded data in order to calculate the relative offsets and skews. A Kalman filter is used here to optimally estimate these parameters. The discrete system state vector for the j^{th} micro-satellite is defined as

$$\underline{x}_j(k) = \left[\alpha_1(k) \;\; \beta_1(k) \;\; \cdots \;\; \alpha_{N-1}(k) \;\; \beta_{N-1}(k)\right]^T \tag{2}$$

where $\alpha_i(k)$ and $\beta_i(k)$ are the relative phase offset and clock skew of the j^{th} to i^{th} micro-satellite, $i \neq j$. The state transition of the system can be described by

$$\underline{x}_j(k+1) = A \cdot \underline{x}_j(k) + \underline{w}_j(k) \tag{3}$$

where A is the transition matrix and represented by a $2(N-1)\times 2(N-1)$ identity matrix and $\underline{w}_j(k)$ is the driving noise (zero mean white Gaussian noise) and characterized by its covariance matrix $Q_j(k)$

$$E\left\{\underline{w}_j(k)\right\}=0$$
$$E\left\{\underline{w}_j(k),\underline{w}_j(k+\tau)^T\right\}=Q_j(k)\cdot\delta(\tau) \tag{4}$$

The system is observed through a measurement that gives an $(N$-1)-dimensional vector $\underline{z}_j(k)$ written as

$$\underline{z}_j(k)=H_j(k)\cdot\underline{x}_j(k)+\underline{v}_j(k) \tag{5}$$

The matrix $\mathrm{H}(k)$ is composed of constant values and has dimension $(N-1)\times 2(N-1)$

$$H(k)=\begin{bmatrix}1 & T_{rj,k} & 0 & 0 & 0 & \cdots & 0 & 0\\ 0 & 0 & 1 & T_{rj,k} & 0 & \cdots & 0 & 0\\ \vdots & \vdots & & & & & \vdots & \vdots\\ 0 & 0 & 0 & \cdots & 0 & 0 & 1 & T_{rj,k}\end{bmatrix} \tag{6}$$

where $T_{rj,k}$ is the time-scale of the j^{th} satellite. The *(N-1)*-dimensional vector $\underline{v}_j(k)$ represents the measurement noise, given by zero mean white Gaussian noise and covariance matrix R. Such a noise is independent of the past and of the other noises described by $\underline{w}_j(k)$. Thus

$$E\left\{\underline{v}_j(k),\underline{v}_j(k+\tau)^T\right\}=R_j\cdot\delta(\tau)$$
$$E\left\{\underline{v}_j(k),\underline{w}_j(k+\tau)^T\right\}=0 \tag{7}$$

By using a Kalman filter there is also a possibility to calculate the minimum number of broadcasts such that the estimated parameters deviate within a given value (e.g. 1%). This means that the number of broadcast N has to fulfill the following condition $E\left\{(\hat{\alpha}-\alpha)^2\right\}\le 0.01^2\sigma_\alpha^2$ and $E\left\{(\hat{\beta}-\beta)^2\right\}\le 0.01^2\sigma_\beta^2$ and $E\left\{(\hat{\gamma}-\gamma)^2\right\}\le 0.01^2\sigma_\gamma^2$. The diagonal entries of P give the minimum mean square errors $E\left\{(\hat{\alpha}-\alpha)^2\right\}$, $E\left\{(\hat{\beta}-\beta)^2\right\}$ and $E\left\{(\hat{\gamma}-\gamma)^2\right\}$. We can find the smallest N such that the diagonal entries of P are less than or equal to the desired variances which can be done numerically.

V. KALMAN FILTERING ALGORITHM

Once having found the state space and observation model, the Kalman filter is readily formulated. The Kalman filter algorithm [7] is given by the following two sets of equations

Time Update (Predict)

$$\hat{\underline{x}}_{k+1}^{-}=A\cdot\hat{\underline{x}}_{k}^{+}$$
$$P^{-}(k+1)=A\cdot P^{+}(k)\cdot A^{\mathrm{T}}+Q(k) \tag{8}$$

Measurement Update (Correct)

$$K(k+1)=P^{-}(k+1)\cdot H^{\mathrm{T}}(k+1)\cdot\left[H(k+1)\cdot P^{-}(k+1)\cdot H^{\mathrm{T}}(k+1)+R(k+1)\right]^{-1}$$
$$\underline{r}_{k+1}=\underline{y}_{k+1}-H(k+1)\cdot\hat{\underline{x}}_{k+1}^{-} \tag{9}$$
$$\hat{\underline{x}}_{k+1}^{+}=\hat{\underline{x}}_{k+1}^{-}+K(k+1)\cdot\underline{r}_{k+1}$$
$$P^{+}(k+1)=P^{-}(k+1)-K(k+1)\cdot H(k+1)\cdot P^{-}(k+1)$$

The above sets of equations are recursively computed. The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the *a priori* estimates for the next time step. The measurement update equations are responsible for the feedback, i.e. for incorporating a new measurement into the *a priori* estimate to obtain an improved *a posteriori* estimate.

VI. SIMULATION

The simulation is done by synthetic data. This example assumes one master satellite and three micro-satellites as in Fig. 2. Clocks in micro-satellites run at different offsets and rates. Moreover, the line-of-sight from one satellite to all others must be always available. Each satellite performs Kalman filtering to estimate the clock offsets and skews relative to all others. The standard deviation of the time-stamping process is the same in all micro-satellites. The simulation is done for micro-satellite 1. However, the process of relative clock parameters estimation is the same for all micro-satellites.

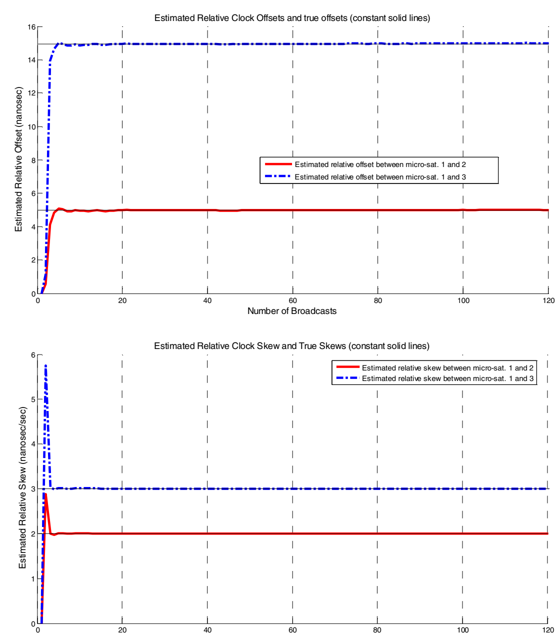

Fig. 3: Relative offset and skew estimated for one satellite

The simulation results show that the estimated relative clock offsets and skews converge to the true values after a small number of synchronization pulses. The relative estimated parameters (offsets and skews) are used for the plotting of the conversion lines to convert the time-scale of micro-satellite 1 to time-scale of micro-satellite 2 and 3 as shown in Fig. 4. The estimated offsets become the intercept points and the corresponding estimated skews are the slops of the lines.

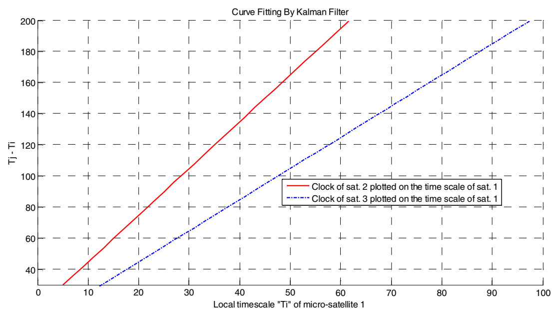

Fig. 4: Conversion lines to convert time-scale of micro-sat. 1 to 2 and 3

VII. CONCLUSION

In this paper, we propose a time synchronization algorithm which can correct or convert both relative phase offsets and clock skews between the micro-satellites for future satellite networks. The use of a Kalman filter to find the best fit line over the observations gives us the possibility not only to convert between local time of the micro-satellites in the network but also to include more independent state measurements for further accuracy improvement. Moreover, applying a proper demodulation technique to the signal received via the inter-satellite link, the relative phase and frequency offsets caused by both clock and moving platforms (Doppler offset) can be extracted. The proposed algorithm in this paper can also be extended to networks with more than one cluster if the cross-link communication between clusters is available.

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