

Time Synchronization for LEO Satellites Positioning in GNSS Resilient Systems

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Abstract—Low Earth orbit (LEO) satellites have attracted attention as a new navigation system due to their ability to provide stronger signals compared to medium Earth orbit (MEO) satellites. However, severe clock errors in LEO satellites degrade positioning accuracy, as clock biases distort signal propagation time and cause range estimation errors. Therefore, periodic clock correction using existing Global Navigation Satellite Systems (GNSS) is required for positioning with LEO satellites. Reliance on GNSS undermines the resilience of LEO satellite positioning systems, since any disruption or manipulation of GNSS signals directly degrades their performance. Consequently, the absence of a trusted timing reference remains a critical vulnerability for LEO-based positioning. To address this issue, we proposed a method to improve positioning accuracy through clock synchronization of LEO satellites using clock information exchange over inter-satellite link (ISL). The proposed method compensate for clock errors between adjacent satellites through distributed average consensus. Simulation results demonstrate that the proposed method reduces positioning errors regardless of the satellite clock type.

Index Terms—Positioning, Inter-satellite link, LEO satellite, Distributed average consensus, Time synchronization

I. INTRODUCTION

Compared to medium Earth orbit (MEO) satellites utilized in conventional global navigation satellite systems (GNSS), low Earth orbit (LEO) satellites operate at lower altitudes, enabling stronger signals and lower propagation delay. In addition, The higher signal strength of LEO satellites improves positioning performance by enhancing tracking stability. These advantages make LEO satellites a promising solution for next-generation navigation systems [1]. However, significant satellite clock errors in LEO satellites lead to misalignment among satellite clocks, resulting in large positioning errors [2]. Furthermore, in the absence of GNSS corrections, positioning accuracy may degrade exponentially. Reliance on GNSS undermines the resilience of LEO satellites positioning systems, since any disruption or manipulation of GNSS signals directly degrades their performance.

To address this issue of positioning using LEO satellites, a satellite clock error correction scheme is introduced. [3], [4] present methods that synchronize all satellites, while [5] proposes a scheme that corrects satellite clocks using GNSS signals. Although these approaches provide valuable insights, they often involve high computational complexity or rely on GNSS availability. Therefore, there is a need for time

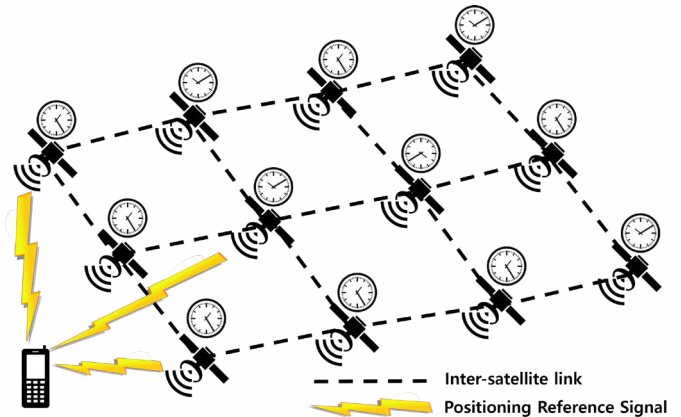


Fig. 1: LEO satellite positioning and timer

synchronization methods that are both independent of GNSS and computationally efficient.

Time synchronization is required only for satellites involved in transmitting signals from four or more satellites during positioning. In positioning with LEO satellites, the satellites visible to a user terminal are typically located close to each other within the constellation. Therefore, time synchronization between closely spaced satellites is essential. In this paper, we propose a time synchronization method for LEO satellites based on clock sharing between satellites connected via inter-satellite link (ISL) as illustrated in Fig. 1. The clock information from adjacent satellites is continuously obtained through ISL information exchange, and time synchronization is performed using this information [6]. The proposed method achieves more accurate time synchronization between satellites that are closer in distance, thereby improving positioning accuracy. In addition, the positioning performance of the proposed time synchronization method is analyzed.

The remainder of this paper is organized as follows. In Session II, explain the proposed satellite clock error compensation method. In Session III, we analyze the performance of the proposed time synchronization method. Finally, in Session IV, we conclude this paper and discuss future work.

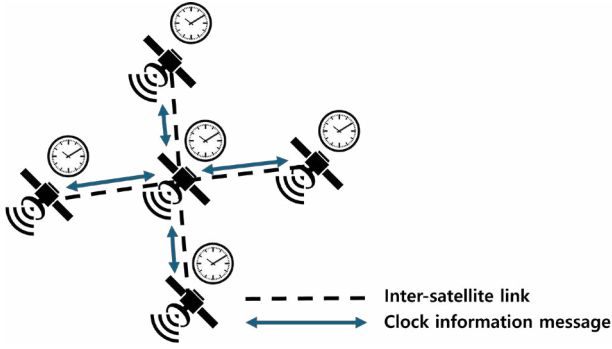


Fig. 2: LEO satellite ISL and clock information message

II. SATELLITE CLOCK SYNCHRONIZATION METHOD

In Session II, we explain the proposed satellite clock error compensation method using ISL clock information exchange.

A. Proposed LEO ISL Positioning system model

As shown in Fig. 2, LEO satellites periodically exchange clock information with satellites connected through ISL. By exchanging timing information, satellites can obtain local timing information from their surroundings without relying on external signals such as GNSS. The satellite reduce relative clock offsets with adjacent satellites using clock information from satellites connected through ISL.

We assume a scenario in which GNSS signals to LEO satellites are interrupted. The satellite clock errors are assumed to follow a Gaussian distribution and are generated as given by the following equation:

$$t_i(t) = t_i^{\text{ideal}}(t) + n_i(t), \quad n_i(t) \sim \mathcal{N}(0, \sigma_i^2), \quad (1)$$

$t_i(t)$ denotes the transmitted clock value of satellite i at time t , which is embedded in the positioning signal. $t_i^{\text{ideal}}(t)$ represents the ideal click reading in the absence of any errors or noise. The term $n_i(t)$ captures the stochastic clock error, which is assumed to follow a zero-mean Gaussian distribution. σ_i^2 indicates the variance of the timing noise specific to satellite i . σ_i^2 differs for each satellite, and in this study, we assume three distinct satellite clocks.

B. Consensus-Based Time Synchronization method

When the satellites used for positioning have unsynchronized clocks, positioning errors increase. Therefore, we propose a consensus-based time synchronization method among adjacent satellites. Satellites analyze clock information using a distributed average consensus algorithm and compensate for clock errors using the time differences of adjacent satellites clocks. The method for correcting each satellite clock is given by the following equations:

$$t_i(t+1) = t_i(t) + \frac{1}{N} \sum_{j \in \mathcal{N}(i)} (t_i(t) - t_j(t)), \quad (2)$$

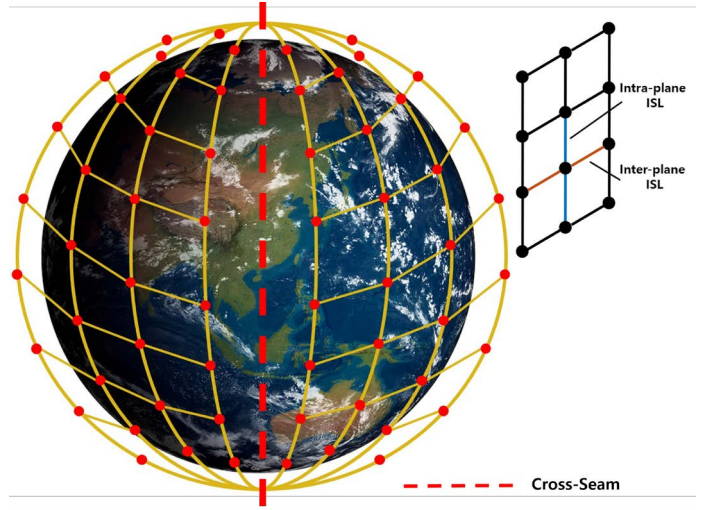


Fig. 3: Walker-Star constellation and ISLs

where $t_i(t)$ is the clock value of satellite i at time index t , $\mathcal{N}(i)$ is the set of satellites that are connected to satellite i via ISL, N is the number of elements in the set $\mathcal{N}(i)$.

III. PERFORMANCE EVALUATION

In Session III, we explain system model demonstrate the results of the proposed time synchronization method. Additionally, the simulation results demonstrate the performance of the proposed method.

As shown in Fig. 3, we assume a scenario in which LEO satellites are deployed in a Walker-Star constellation. Each satellite exchanges clock information via ISL with four adjacent satellites, excluding those located across the Cross-Seam in neighboring orbital planes moving in the opposite direction. We assume a scenario in which positioning is performed for a UE located in Seoul using LEO satellites. Table 1 presents the satellite and ground parameters used in the simulation. The UE performs positioning using satellites that satisfy the minimum elevation angle requirement. Positioning is conducted with the four satellites having the smallest GDOP. Each satellite provides its position and clock information to the UE. The corresponding error characteristics for each clock are summarized in Table. II.

TABLE I: Walker-Star Constellation Parameters for LEO Satellites

Parameter	Value
Number of Orbital Planes	12
Satellites per Orbital Plane	49
Inclination Angle	87.9°
Altitude	1200 km
Minimum Elevation Angle	25°
Phasing factor	6
UE latitude	37.56°
UE longitude	127.00°

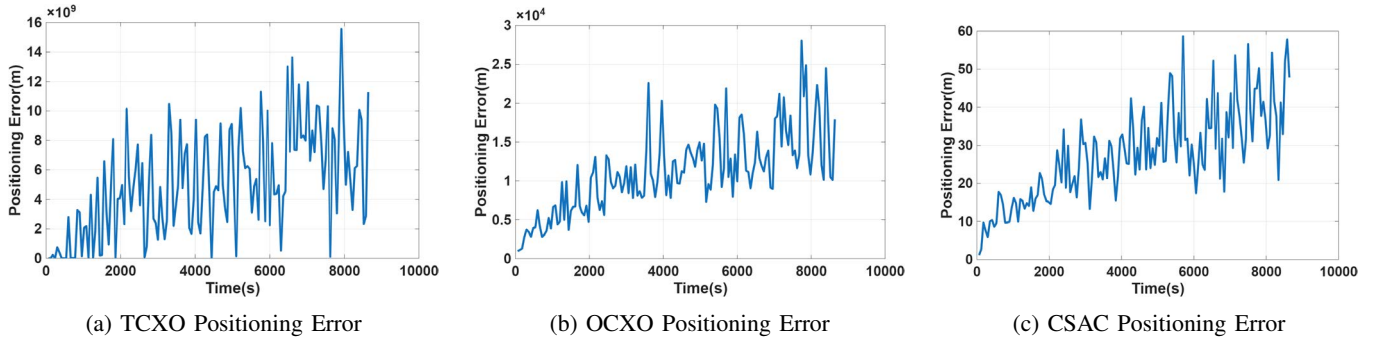


Fig. 4: Positioning error with three satellite clock

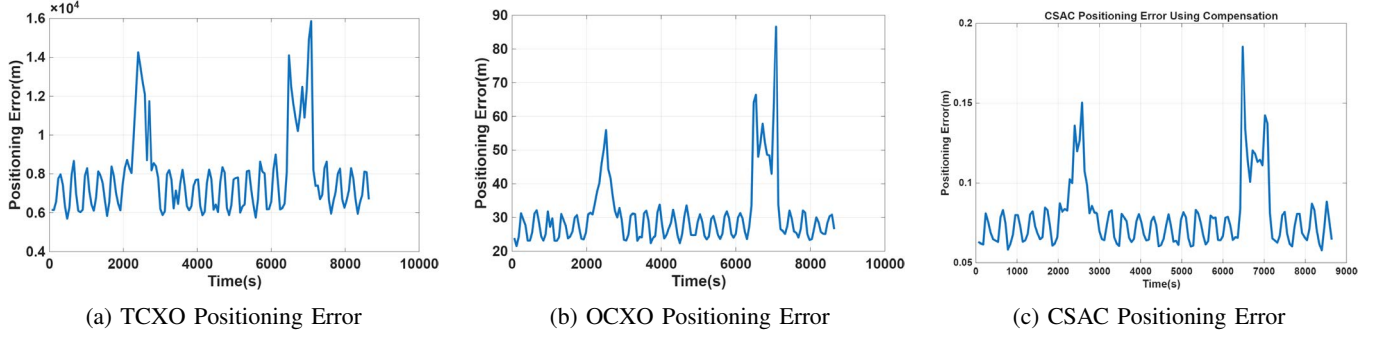


Fig. 5: Positioning error with three satellite clock using proposed method

In the simulation, the results are evaluated using positioning error. Fig. 4 presents the performance evaluation results without satellite clock compensation. In this case, the positioning error increases regardless of the clock characteristics. Fig. 5 shows the performance evaluation results when the proposed method is applied to compensate for satellite clock errors. The positioning error is reduced for all clocks and remains within a certain range. However, in two time periods, the positioning error increases sharply. This occurs when positioning is performed using satellite combinations that are distant in the topology and moving in opposite directions.

These results indicate that positioning errors can be reduced through time synchronization using inter-satellite clock information exchange. Furthermore, the proposed method achieves these improvements with low computational complexity, as it utilizes only the clock information of satellites connected via ISLs.

IV. CONCLUSION

In this paper, we proposed a satellite clock compensation method using ISLs to reduce positioning errors in GNSS-denied environments. The proposed method compensates the

clocks using other satellite clock information, thereby reducing relative clock offsets between satellites and improving positioning accuracy.

In future work, we plan to study weighted time synchronization when only some satellites receive clock corrections.

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TABLE II: Gaussian Distribution Models

Oscillator Type	Model (Gaussian Distribution)
TCXO	$\mathcal{N}(0, (1.72 \times 10^{-6})^2)$
OCXO	$\mathcal{N}(0, (6.7 \times 10^{-9})^2)$
CSAC	$\mathcal{N}(0, (1.67 \times 10^{-11})^2)$