Positioning and Navigation Methods Based on Starlink Signals: A Comprehensive Review

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Abstract—**This paper provides a comprehensive review of recent advancements in positioning and navigation methods utilizing signals from Starlink, a prominent Low Earth Orbit (LEO) satellite network. The review covers a range of research topics, including Doppler shift analysis [1], Orthogonal Frequency Division Multiplexing (OFDM) signal processing, and cognitive navigation frameworks [2]. The paper aims to serve as a valuable resource for researchers and practitioners in the field, highlighting the potential and challenges associated with leveraging Starlink signals for precise positioning and navigation.**

I. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are essential for modern navigation and positioning needs. However, in environments such as urban canyons and dense vegetation areas, GNSS signals can be obstructed or interfered, leading to reduced accuracy [3]. The development of LEO satellite networks like Starlink offers new opportunities for enhancing positioning and navigation capabilities. Starlink, as one of the representative LEO satellite networks, has become a focal point of research due to its signal characteristics and positioning potential. This paper reviews recent studies that propose multiple positioning methods based on Doppler shifts and OFDM signals and validate their effectiveness through simulations and experiments [4].

II. LITERATURE REVIEW

This section provides an extensive review of the literature related to positioning and navigation methods based on Starlink signals, focusing on Doppler shift analysis, OFDM signal processing, and cognitive navigation frameworks.

A. Doppler Shift Positioning Methods for Starlink Signals

Literature 1-4 propose positioning methods based on Doppler shifts, aimed at solving positioning issues in dynamic target navigation. The goal is to achieve high-precision positioning, especially in environments where GNSS signals are unavailable.

Methodology:

1) **Signal Analysis:** Study signal characteristics.
2) **Mathematical Modeling:** Based on Doppler shifts and relative target velocity.
3) **Experimental Verification:** Test navigation accuracy in dynamic environments.

Formulas and Analysis:

Doppler Shift Formula:

$$f_D = \frac{(\mathbf{v}_s - \mathbf{v}_r) \cdot (\mathbf{r}_s - \mathbf{r}_r)}{\|\mathbf{r}_s - \mathbf{r}_r\|} \cdot \frac{f_c}{c} \tag{1}$$

Analysis: Utilizes the relative velocity and position between satellites and receivers to calculate Doppler shifts.

Error Sensitivity Formula:

$$\sigma^2 = \sum_i \left(\frac{\partial f_D}{\partial x_i} \cdot \sigma_{x_i} \right)^2 \tag{2}$$

Analysis: Quantifies the overall impact of various error sources on Doppler trajectories.

Doppler Shift Formula:

$$f_D = \frac{\partial r(t)}{\partial t} \cdot \frac{f_c}{c} \tag{3}$$

Analysis: Reflects the change in frequency due to the relative motion between the satellite and the receiver.

Velocity Estimation Formula:

$$v_r = \frac{\Delta f_d \cdot c}{f_c} \tag{4}$$

Analysis: Estimates the receiver's velocity based on the Doppler shift.

Figures:

Figure 1 illustrates the identified pilot signals of Starlink, clearly indicating the frequency distribution (11.325 GHz and 11.575 GHz) and the characteristics of the pilot signals [3]. This information forms an essential part of the signal's basic structure.

Figure 2 displays a waterfall diagram collected by a spectrum analyzer for the 11.325 GHz pilot signal, dynamically reflecting the changes in signal spectra over time. It intuitively showcases the dynamic characteristics of the signal and the impact of Doppler shifts.

B. Cognitive Navigation with OFDM Signals

Literature 5 and 6 discuss a cognitive navigation framework based on OFDM signals, aiming to detect and navigate unknown OFDM signals.

Research Objective: Achieve cognitive navigation of Starlink signals with positioning accuracy reaching 6.5 meters in dynamic environments.

Methodology:

1) **Signal Modeling:** Analyze OFDM subcarrier structure and spectral characteristics [4].
2) **Feature Extraction:** Use Maximum Likelihood Estimation to obtain signal features.
3) **Experimental Verification:** Verify performance in UAV and vehicle navigation experiments.

Formulas and Analysis:

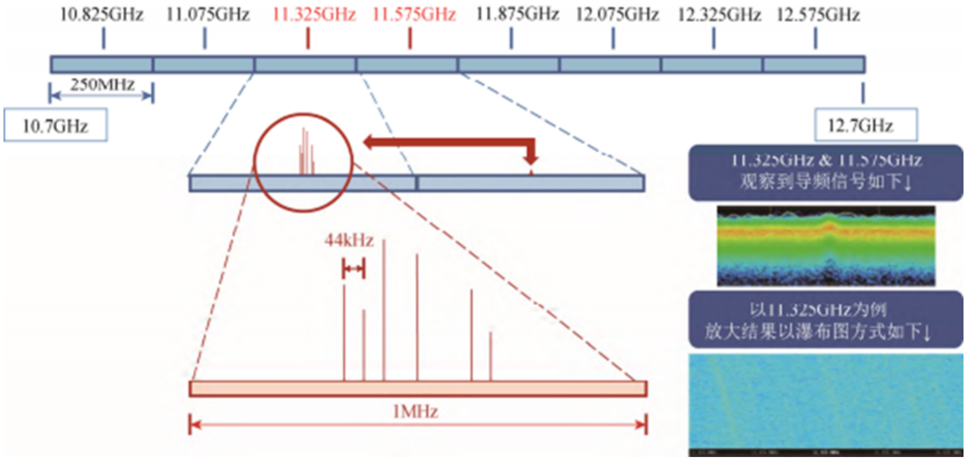

Fig. 1. The identified pilot signal schematic of Starlink

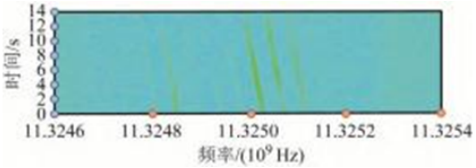

Fig. 2. The 11.325 GHz pilot signal waterfall diagram captured by a spectrum analyzer

1. OFDM Subcarrier Frequency Formula:

$$f_i = f_0 + i \cdot \Delta f \tag{5}$$

Analysis: Describes the linear distribution of subcarrier frequencies, with Δf as the subcarrier interval.

2. Signal Correlation Formula:

$$R(\tau) = \int_{-\infty}^{\infty} r(t) r^*(t - \Delta\tau) \mathrm{d}t \tag{6}$$

Analysis: Used to obtain the duration of OFDM signals, facilitating synchronization and positioning [5].

3. Frequency Change Formula:

$$\Delta f = \frac{\Delta v}{\lambda} \tag{7}$$

Analysis: Calculates the change in frequency based on velocity change.

4. Frame Length Formula:

$$L = \frac{1}{\Delta f} \tag{8}$$

Analysis: Estimates the frame length of the signal based on the subcarrier frequency interval.

Figures:

Figure 3 demonstrates how Doppler shifts are determined by the time-frequency characteristics of the signal, aligning with the typical features of OFDM signal time-frequency distribution [4].

Figure 4 presents the results of positioning based on a combination of Doppler and pseudorange data, highlighting the improved accuracy achieved through Doppler positioning.

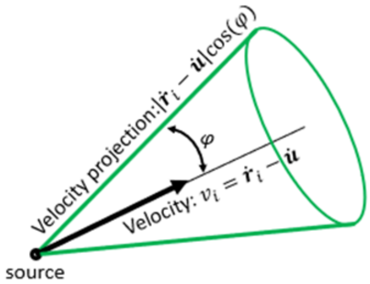

Fig. 3. Doppler Shift Measurement

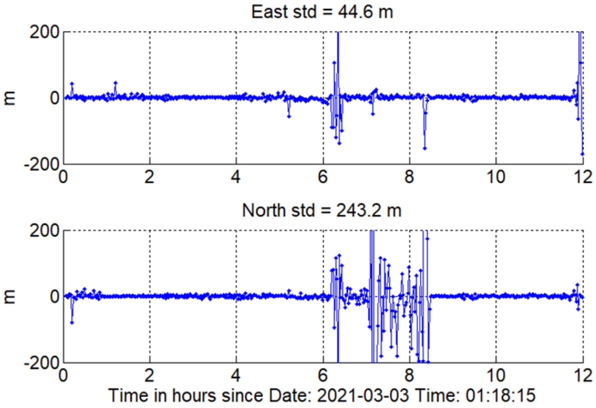

Fig. 4. Vertical-aided DPR Solution with Collected GPS Measurement Data

C. Doppler Positioning with Starlink Signals

Literature 7 and 8 focus on Doppler-based positioning methods, particularly for LEO satellite signals.

Research Content:

Explore the positioning potential of unknown LEO satellite signals in dynamic target navigation and construct dynamic positioning methods based on Doppler observations.

Research Objective: asa

Provide high-precision positioning under GNSS shooting conditions and verify the effectiveness of Doppler shift models.

Methodology:

1) **Model Design:** Construct Doppler positioning equations and analyze error sources.
2) **Error Modeling:** Assess the impact of orbit errors and time drift on positioning results [6].
3) **Simulation Experiment Verification:** Simulate flight navigation scenarios and verify algorithm performance.

Formulas and Analysis:

Doppler Shift Formula:

$$f_D = \frac{\partial \mathbf{r}}{\partial t} \cdot \frac{f_c}{c} \tag{9}$$

Analysis: Combines orbit velocity estimation with Doppler measurements to improve positioning accuracy.

Orbit Error Model:

$$\Delta r_s = A_0 + A_1 \cdot \Delta t + A_2 \cdot (\Delta t)^2 \tag{10}$$

Analysis: Uses a quadratic model to describe changes in orbit error over time.

Doppler Error Correction Formula:

$$f_{D,meas} - f_{D,model} = \Delta f_D \tag{11}$$

Analysis: Corrects positioning errors by comparing observed and modeled Doppler shifts.

Orbit Error Correction Formula:

$$\Delta r_s = r_{\text{pred}} - r_{\text{true}} \tag{12}$$

Analysis: Compares predicted and actual orbit positions to improve the model.

Figures:

Figure 5 shows the trajectory distribution of simulated dynamic targets (e.g., a high-speed aircraft) and six Starlink satellites, aligning with the description requirements of a dynamic navigation trajectory diagram [7].

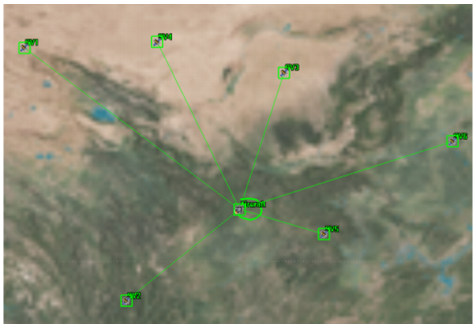

Fig. 5. The simulated aircraft and six LEO satellites for positioning

Figure 6 illustrates the GDOP value changes of six satellites during navigation using Doppler positioning. GDOP values reflect the impact of geometric distribution on positioning accuracy, matching the requirements for a sensitivity analysis diagram.

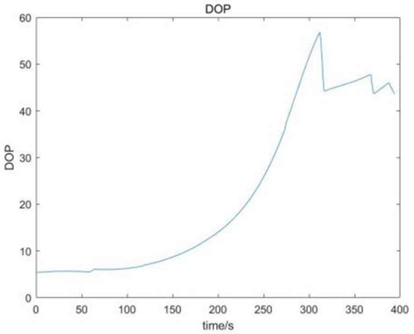

Fig. 6. GDOP for six Starlink satellites

D. OFDM Structure Analysis of Starlink Signals

Literature 9 and 10 reveal the OFDM structure of Starlink signals and propose positioning methods based on this structure.

Methodology:

1) **Signal Modeling:** Analyze the frame length and reference signal structure OFDM signals [8].
2) **Signal Processing:** Use coherent correlation methods to calculate frame length and synchronize.
3) **Experimental Verification:** Analyze the performance after fusing signals from multiple satellites [9].

Formulas and Analysis:

OFDM Frame Length Estimation Formula:

$$L = \frac{1}{\Delta f} \tag{13}$$

Analysis: Calculates frame length based on subcarrier intervals for signal synchronization.

Autocorrelation Signal Model:

$$R(\tau) = \int_{-\infty}^{\infty} r(t) r^*(t - \tau) \mathrm{d}t \tag{14}$$

Analysis: Extracts signal frame periods through autocorrelation functions.

Geometry Impact Formula:

$$\Delta\theta = \sqrt{\Delta r_s^2 + \Delta r_L^2} \tag{15}$$

Analysis: Describes the impact of satellite geometry on positioning accuracy.

Figures:

Figure 7 provides a detailed illustration of the Starlink OFDM frame structure, including signal symbol duration, guard intervals, and frequency spacing. These features depict the core structure of OFDM signals [8].

Figure 8 shows the variation of positioning errors during tests.

Figure 9 illustrates the changes in DPDOP values during tests, explaining how satellite geometric configurations affect positioning accuracy. Together, these two figures comprehensively describe the sources and impacts of errors in Starlink positioning.

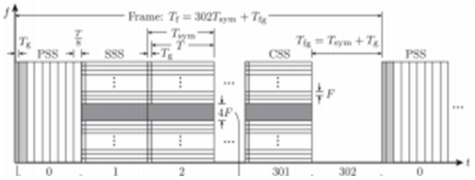

Fig. 7. The frame structure of Starlink OFDM signals

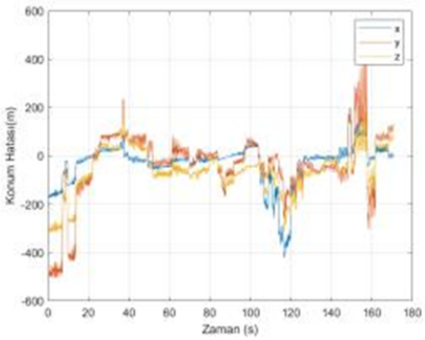

Fig. 8. Test-1 Konum Hatalan

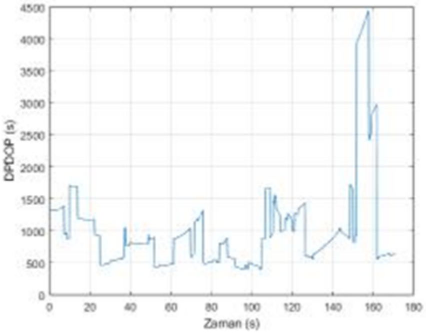

Fig. 9. The changes in DPDOP values during tests

III. Conclusion

The comprehensive review presented in this document underscores the significant potential of leveraging Starlink signals for positioning and navigation. By exploring Doppler shift-based methods, cognitive navigation frameworks utilizing OFDM signals, and advanced error correction techniques, this study highlights the viability of Starlink as an alternative or complement to GNSS in challenging environments [6].

The review demonstrates that:

- Doppler shift positioning methods provide robust solutions for dynamic navigation, achieving high accuracy even in GNSS-denied scenarios [1].
- OFDM signal structures enable precise synchronization and positioning, enhancing the overall reliability of the system [2].
- Error modeling and correction play a critical role in improving the accuracy and robustness of Starlink-based navigation solutions.

Future work should focus on:

- Mitigating error sources, including orbit prediction inaccuracies and signal interference.
- Integrating Starlink signals with other sensor systems to enhance reliability and applicability across diverse environments.
- Extending experimental validation to real-world applications involving high-dynamic platforms such as UAVs and autonomous vehicles.

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