Performance Analysis of LEO Satellite-Based Positioning Algorithms Using Sionna

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Abstract

Global navigation satellite systems (GNSS) have less signal strength in urban and indoor environments due to their long altitude above the Earth, as they use medium Earth orbit (MEO) satellite constellations. Low Earth orbit (LEO) satellite constellations are an alternative in those scenarios, as LEO satellites have better signal strength than GNSS. However, urban areas have complex signal propagation environments due to high-rise buildings and obstacles. For evaluating the performance of positioning algorithms in such a complex environment, a powerful ray tracing, like Sionna, can provide a replica of a real-time environment. In this study, we compare the positioning outcome of LEO satellite-based positioning algorithms to demonstrate their reliability in real-time complex environments. The comparison results confirm that the 3DPose framework performs better than other positioning algorithms.

Ⅰ. Introduction

In the outdoor positioning system context, satellite-based positioning is popular because it provides position in the global reference frame. Global navigation systems (GPS), Galileo, Beidou, and GLONASS provide services globally under the umbrella of the global navigation satellite system (GNSS). The signals from GNSS satellites are diffracted by large buildings and other natural obstacles. This causes multipath and non-line-of-sight (NLOS) signal reception. Due to the high altitude of GNSS satellites that use medium Earth orbit (MEO), GNSS signal strength is low in urban and indoor environments. GNSS positioning performance in multipath and NLOS environments is analyzed in [1].

The growing constellation of low Earth orbit (LEO) satellites offers 30 dB more signal strength than the GNSS satellites. Though LEO satellites are designed for communication purposes, they have potential in navigation applications utilizing a signals of opportunity (SOPs)-based approach [2]. In urban environments, non-line-of-sight (NLOS) signal reception often induces errors in measuring navigation observables like Doppler shift, pseudorange, and carrier phase. The measurement errors contribute to the positioning error of the user terminal (UT). An efficient ray tracing algorithm, like Sionna [3], can model the NLOS signal propagation path in complex urban environments, considering the 3-dimensional (3D) building of the environment.

Sionna is a hardware-accelerated differentiable open-source library based on TensorFlow, integrated with a differential ray tracer. It can fully exploit hardware resources such as NVIDIA GPUs. The Sionna ray tracing utilizes Mitsuba 3 for handling the 3D environmental data and just-in-time compiler Dr.Jit. Fig. 1 shows the signal propagation path from satellite to UT using Sionna ray tracing. In this paper, we focus on evaluating existing LEO satellite-based positioning algorithms with a simulation environment using Sionna.

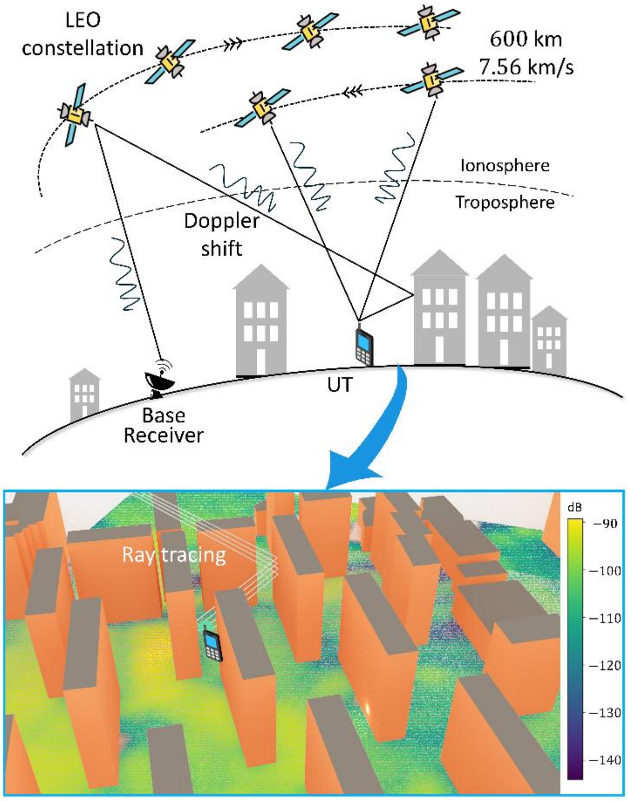

Fig. 1: Ray tracing using Sionna and LEO satellite-based Positioning.

Ⅱ. Positioning Algorithms

In LEO satellite-based positioning utilizing the SOPs approach, UT extracts the navigation observables like Doppler shift and carrier phase from the communication signals. The frequency of the received signal changes due to the high relative motion between the satellite and UT, which is known as the Doppler shift. In SOPs-based approaches, the position and velocity of the LEO satellites are estimated with a two-line element (TLE) file, which induces error over time known as ephemeris error [2]. This ephemeris error causes a remarkable positioning error of UT. Thus, a base receiver is used to compensate for the ephemeris error in differential Doppler positioning. Utilizing measurements from a base receiver, the corrected Doppler shift measurement (Δf_{d}) for the static UT is as follows [4].

$$\Delta f_{\mathrm{d}}\lambda = \mathbf{v}_{\mathrm{sat}} \cdot \frac{\mathbf{x}_{\mathrm{sat}}-\mathbf{x}_{\mathrm{ut}}}{\|\mathbf{x}_{\mathrm{sat}}-\mathbf{x}_{\mathrm{ut}}\|} + \delta f_{\mathrm{d}}\lambda + \epsilon, \quad (1)$$

where $\mathbf{x}_{\mathrm{sat}}$ and $\mathbf{v}_{\mathrm{sat}}$ are the position and velocity of the LEO satellite. $\mathbf{x}_{\mathrm{ut}}$, Δf_{d}, δf_{d}, λ, and ϵ are the UT position, corrected Doppler shift measurements, residual Doppler shift error due to the effect of ephemeris error, wavelength of transmitted signal, and other errors, respectively.

The effect of ephemeris error in the Doppler shift measurement is not fully compensated in differential Doppler positioning. The 3DPose framework [2] further refines the Doppler shift measurements using an ephemeris error correction algorithm. The residual Doppler shift error due to the effect of ephemeris error is as follows [2].

$$\delta f_{\mathrm{d}}\lambda = \hat{f}_{\mathrm{d}}\lambda\left(\frac{\hat{r}}{r} - 1\right) + \frac{\|\mathbf{v}_{\mathrm{sat}}\|\|\Delta\mathbf{x}_{\mathrm{sat}}\|}{r} \quad (2)$$

where $\hat{f}_{\mathrm{d}}$ and $\Delta\mathbf{x}_{\mathrm{sat}}$ are the estimated Doppler shift and ephemeris error of the satellite. $\hat{r}$ and r are the estimated and true ranges between UT and the satellite.

III. Result and Discussion

This section presents the comparison of positioning results for the double-difference (DD) carrier phase positioning, differential Doppler positioning, and 3DPose framework in terms of 3D root mean square error (RMSE). The simulation environment with 3D building structure is created with the help of Blender and OpenStreet Map tools. The signal propagation path is simulated with the open-source library Sionna ray tracing. The evaluation result is tabulated in Table 1.

Table 1. Comparison of positioning results.

Positioning Algorithm	3D positioning RMSE (m)
DD carrier phase positioning [5]	9.29
Differential Doppler positioning [4]	4.48
3DPose framework [2]	**0.88**

Errors are induced in the pseudorange measurement due to multipath and NLOS conditions. DD carrier phase positioning [4] achieves an RMSE of 9.29 m. However, multipath has less effect on the Doppler shift measurement error. The RMSE of differential Doppler positioning is 4.48 m. The 3DPose framework [2] achieves an RMSE of 0.88 m by applying the ephemeris error correction algorithm.

IV. Conclusion

The use of LEO satellites in positioning applications increases interest among researchers due to their advantages over GNSS. Sionna is an open-source library that is beneficial in modeling the signal propagation path of LEO satellites in urban environments. This paper presents an analysis of the performance of positioning algorithms in urban environments utilizing Sionna ray tracing. The evaluation result confirms that the 3DPose framework demonstrates superior positioning performance even in the case of complex urban environment.

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