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Performance Improvement Provided by Global Navigation Satellite System Foresight Geospatial Augmentation in Deep Urban Environments †

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Abstract: Global navigation satellite systems (GNSSs) are an integral part of global positioning. However, because GNSS performance is impacted by signal obscuration and the presence of multipath in urban and deep urban environments, it is not accurate, reliable, and widely available enough to be a standalone system in all environments. This creates two problems: (1) the GNSS user does not know when or where GNSS performance may be degraded and (2) the GNSS user has limited ability to mitigate these issues. No mitigation strategy exists to improve the availability of GNSSs themselves. Inertial measurement units (IMUs) and sensor fusion provide other costly methods to improve positioning performance, but most systems still rely on GNSSs for absolute position. Spirent's GNSS Foresight service aims to solve both issues. As a cloud-based solution, GNSS Foresight provides satellite and signal information, and this can be employed to support the decision-making strategy and calculations in the GNSS receiver to improve its positioning solution performance, integrity, and reliability. In this paper, GNSS Foresight is introduced, and a performance evaluation of GNSS Foresight in dense urban areas is presented. Using the data collected from two urban areas in North America, we evaluated GNSS Foresight and compared the performance of GNSS positioning solutions with and without Foresight-aided data. The comparison results show the observed improvements in GNSS receiver operation. Foresight can also be used to develop measurement engine performance enhancements in the acquisition of new satellites and the tracking/re-acquisition of current satellites using line-of-sight (LOS) satellite information. In the positional computation process, Foresight enables receivers to prioritize LOS signals over degraded non-line-of-sight (NLOS) signals, hence significantly reducing positioning errors and outperforming conventional GNSS positioning, particularly in difficult urban environments.

Keywords: GNSS augmentation; multi-constellation; performance improvement; urban environments; line of sight; geospatial augmentation

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1. Introduction

1.1. The Problem—GNSS Navigation in Urban Areas

GPSs were developed over 40 years ago and are used in many different applications. Many of these applications are pushing the requirements of GNSS technology further than ever before. The concept of GNSS technology is that the GNSS receiver measures its distance from the satellite by calculating the time it takes for the GNSS signal to travel from the satellite to the receiver. The receiver needs four or more satellites to compute its position, velocity, and time [1].

GNSS signal reception is challenging in urban environments such as downtown areas and city centers due to frequent blockage of line-of-signal GNSS signals by obstructions such as tall buildings, overpasses, and bridges. The unpredictability of GNSS availability and its accuracy in urban environments has been a persistent problem in GNSSs. GNSS performance is unpredictable due to signal obscuration and the presence of multipath in deep urban environments. As shown on the left in Figure 1, signal obscuration occurs when GNSS satellite signals are blocked by buildings and only satellites that are high in the sky are visible to the GNSS receiver. Constellations formed by those few high-elevation satellites, however, have poor dilution of precision (DOP) values.

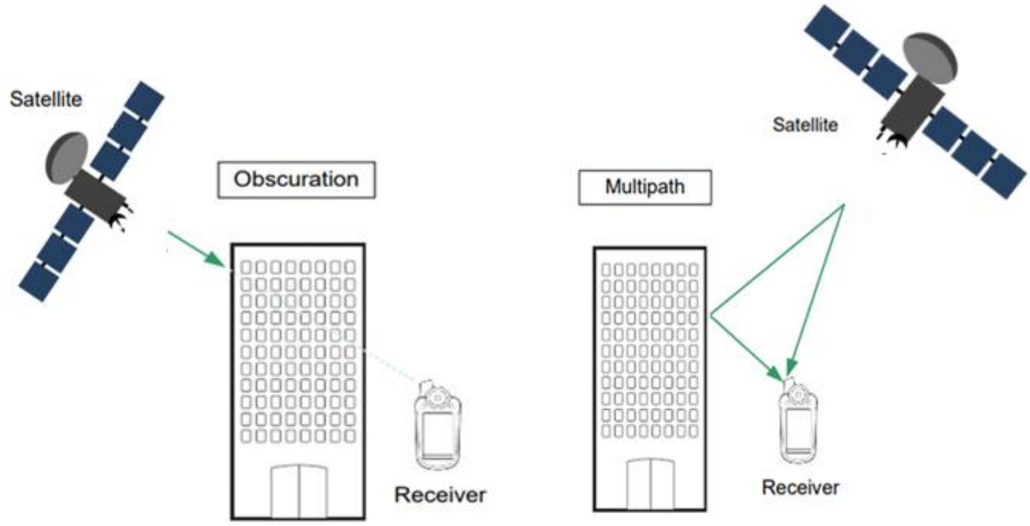

Figure 1. Signal obscuration/non-line of sight and multipath.

GNSS multipath refers to the phenomenon of when satellite signals are reflected by buildings before reaching the GNSS receiver, as shown on the right in Figure 1. Such reflections can cause significant errors in user navigation solutions. The accuracy of the computed position is dependent on the quality of the signals received by the receiver and on the geometry of the satellites in view [2].

1.2. The Problem—Which Satellites Do You Use?

Currently, there are four major GNSS constellations, and in the last ten years, the number of GNSS satellites has increased by over 50% to over 120 GNSS satellites. The increase in the number of GNSS satellites improves satellite availability. In a typical urban environment, the GNSS receiver will acquire many GNSS satellites; however, only a few of these measurements will be line of sight (LOS), while the others will be non-line of sight (NLOS).

As an example, in a drive test in downtown Indianapolis, the drive trial started in a fairly open sky area (the orange arrow in Figure 2 below), and from the start of the SNR plot in Figure 3, it is easy to see which GNSS measurements are LOS signals and which ones are NLOS signals. LOS signals tend to have a higher SNR than NLOS signals. As the car drives into the built-up area, there is then a considerable overlap between the LOS signals and the NLOS signals, and it becomes difficult to distinguish between the LOS and NLOS signals. In this situation, it is difficult for the receiver to decide on which satellites to use in computing its position.

With the truth data and some post-processing tools, the LOS and NLOS signals were worked out, as shown in Figure 4. This makes it difficult to use SNR to decide which signals are LOS signals and which signals are NLOS signals.

Figure 2. Drive test in downtown Indianapolis.

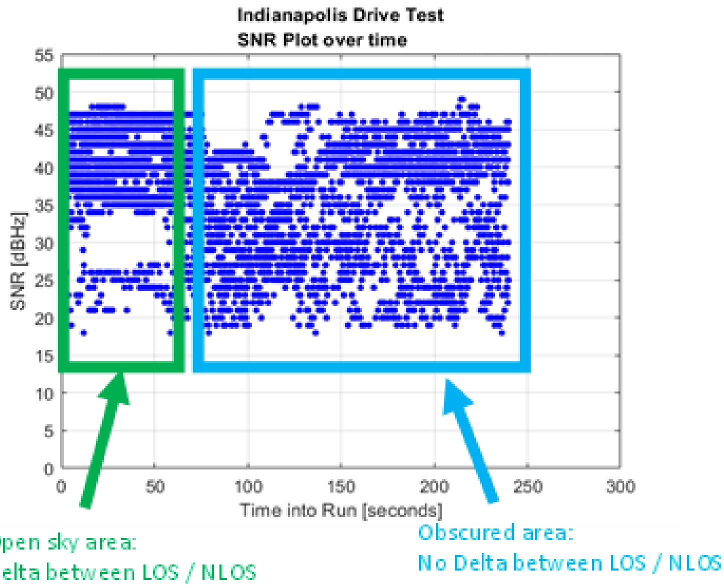

Figure 3. SNR measurements of all GNSS satellites acquired during the Indianapolis drive test.

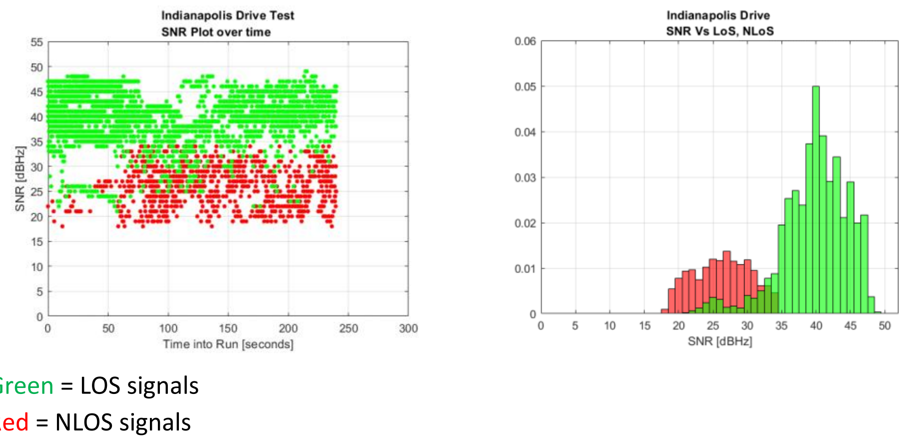

Figure 4. SNR measurement data from the downtown Indianapolis drive test.

Table 1 below highlights this issue: there is an 11 dBHz overlap between LOS and NLOS signals, so a simple cut-off cannot be used to define LOS signals, as it would result in either a significant number of NLOS signals being included or a significant number of LOS signals being excluded.

Table 1. Summary of the minimum and maximum SNR values for the LOS and NLOS signals.

SNR (dBHz)	Max SNR	Min SNR
LOS	45	22
NLOS	33	17

1.3. Review of Approaches to Improve GNSS Position Accuracy

Several techniques have been developed to tackle the problem of navigating GNSSs in urban areas such as:

- Improvements to the GNSS receiver hardware and signal processing algorithms
- Outlier rejection techniques
- The use of sensors
- GNSS shadow matching

1.3.1. Improvements to the GNSS Receiver Hardware and Signal Processing Algorithms

Several changes have been made to the GNSS receiver hardware and algorithms to improve GNSS position accuracy in urban environments. One of the most popular approaches is the use of narrow correlator spacing [3], which reduces the chip spacing between the tracking correlators in the tracking channels in order to mitigate the impact of multipath. Other changes include improvements to the antenna design, the use of wideband filters, and improvements to multipath detection and mitigation algorithms. More recently, the use of super correlation techniques [4] to coherently integrate the GNSS signals for longer in order to make the GNSS receiver more sensitive to the LOS signals than the NLOS signals has been employed. However, these techniques do not provide any external information about the environment and when an NLOS signal is about to become visible or when an LOS signal is about to be obscured.

1.3.2. Outlier Rejection Techniques

Another approach is the use of the outlier rejection technique to improve GNSS position accuracy. These techniques work well when the position engine has lots of measurements. The resulting position solution improves when the error in the measurements is greater than the loss in geometry by excluding satellites. However, when the error is not present in the measurements, this technique could still exclude an LOS signal in error, and this will result in worse geometry and therefore worse position accuracy. This approach does not work well in dense urban environments due to the limited number of satellites available. Also, this approach does not provide any external information about the environment and when an LOS signal is about to become visible or when an LOS signal is about to be obscured.

1.3.3. The Use of Sensors

Sensors can be used to aid GNSS receivers in order to improve their computed position. Sensors work well when they are properly calibrated and if they are started in an open sky area before moving into a dense urban environment. However, sensors do not provide information on how badly contaminated the received GNSS signals are and when an LOS signal is about to become visible or when an LOS signal is about to be obscured.

1.3.4. GNSS Shadow Matching Techniques

Shadow matching is a technique that determines position by comparing the measured signal availability and the SNR with predictions made using a 3D model [5]. However, these techniques do not provide any external information about the environment and when an LOS signal is about to become visible or when an LOS signal is about to be obscured.

A combination of these techniques can be used to improve GNSS position accuracy depending on the GNSS application:

- What equipment is available to the positioning system?
- Does the application require an instantaneous position fix or is it being used for continuous navigation?
- Does the application require future-looking route and mission planning?

2. Spirent's GNSS Foresight

Spirent's GNSS Foresight service provides GNSS users with a forecast of what the GNSS performance is going to be—just like a weather forecast but for GNSSs. This service enables users to know in advance where and when the GNSS is reliable. The Foresight service is a cloud-based service that uses a high-resolution 3D map, combined with precise orbital predictions of where the satellites are to provide LOS visibility for each satellite from current major GNSS constellations. There are two GNSS Foresight services:

(1) The Foresight Live service provides real-time GNSS performance forecast meter by meter every second over the area requested.
(2) The Foresight risk analysis provides a predictive performance analysis of the best- and worst-case GNSS performance for operations and planning.

There are two building blocks for the GNSS Foresight system, as shown in Figure 5:

- The forecast engine is where the forecast calculation is carried out using high-resolution 3D maps and precise satellite orbit information.
- A content delivery network (CDN) is used for fast data delivery. There are three interfaces in the CDN:
    - The ingress API is for receiving the forecast data generated by the forecast engine.
    - The device API is for user devices to request and receive forecast data.
    - The web console is for user configuration and management.

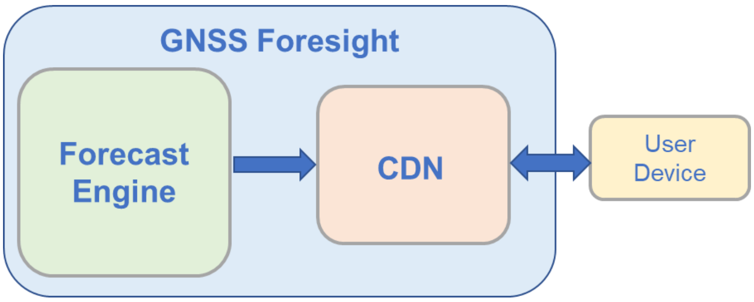

Figure 5. Foresight system architecture.

Following the publication of preliminary results at ION GNSS+ 2022 [6], progress has been made in integrating the data from Foresight with conventional GNSS position solutions.

3. Experimental Data Collection

To understand the performance of the Foresight system under various environmental conditions, we conducted a number of drive tests in two cities in North America. One represents a dense urban environment characterized by tall buildings, skyscrapers, narrow streets, and other obstacles. The other is a light urban environment with fewer buildings, lower building heights, and wider streets. GNSS measurements from multiple constellations (including GPS, GLONASS, BeiDou, and Galileo) were collected in these environments.

The selected dense urban environment is a typical downtown area in North America. The high density of buildings and other structures can cause multipath interference, where signals bounce off buildings and other surfaces before reaching the GNSS receiver, causing errors in the position measurement. Additionally, narrow streets and tall buildings can create "urban canyons" that limit the visibility of GNSS satellites, making it more difficult for the GNSS receiver to obtain a reliable position fix.

In contrast to the dense urban environment, GNSS signals are less likely to encounter multipath interference, and the GNSS receiver can more easily access a sufficient number of GNSS satellites for more accurate positioning in a light urban area. As a result, GNSS performance in a light urban environment is generally better than in a dense urban environment. However, some level of signal obstruction and multipath errors can still occur in the light urban environment due to buildings or other obstructions, especially if the receiver is located in an area with a limited view of the sky.

A mix of survey and consumer grades of GNSS receivers were used in the drive tests. At the beginning of each test, the vehicle was parked at a static open sky location for 15 min to allow the receivers to download ephemeris data and acquire a position fix. The duration of each drive test was 1 h in each environment.

4. Performance Evaluation

4.1. Methodology

With the collected GNSS receiver measurements, matching Foresight LOS satellite information was generated covering the area where the two drive tests were conducted over the testing period. The Foresight LOS information was then used to aid and support the decision-making process, where pseudo-range measurements calculated by NLOS satellites were removed. Therefore, only LOS measurements were passed on to the position and fusion engine to calculate a position fix. Note that in this experimental data set, a location is defined as one where an LOS-only position fix can be produced when there are a minimum of six LOS satellites measured at the location.

Evaluations were performed by comparing the performance aggregated over all locations for which there are positions generated using the following solutions:

- LOS-only with Foresight: The position is computed using LOS measurements only.
- LOS and NLOS measurements: This is a "conventional" GNSS position solution used by receivers that uses both LOS and NLOS measurements to calculate a position fix.

This enables a direct comparison of the benefits of using LOS information provided by the GNSS Foresight service.

4.2. Performance Evaluation

In this section, comparison results are presented for both dense and light urban environments. In particular, cumulative distribution function (CDF) plots are calculated to show the probability distribution of the position errors for the solution with and without Foresight aiding. Figure 6 shows the CDF of the horizontal position error of solutions with and without GNSS Foresight aiding in a dense urban environment. The CDF curves for both solutions are close together at low levels of the position error range, but as the position error increases, the solution without GNSS foresight aiding begins to shift to the right, indicating greater position errors at the percentile of the error distribution. In contrast, the solution with GNSS Foresight aiding remains consistently lower, indicating lower horizontal position error. This difference in position accuracy is particularly noticeable when the position error is less than 10 m, as shown in Figure 7. Overall, both figures provide clear evidence that GNSS Foresight can significantly improve the accuracy of horizontal position estimation.

Table 2 shows the position errors for specific percentiles, computed with and without GNSS Foresight aiding in a dense urban environment. The results show that position errors are significantly lower with GNSS Foresight aiding compared to the LOS + NLOS scenario without GNSS aiding across all computed percentile levels. The table also shows the error reduction in both meters and percentage when using GNSS Foresight data, which indicates that using GNSS Foresight data can lead to a 20–77.9% reduction in position error, depending on the percentile. Overall, these results confirm that incorporating

GNSS Foresight can significantly improve the accuracy of position estimation in a dense urban environment.

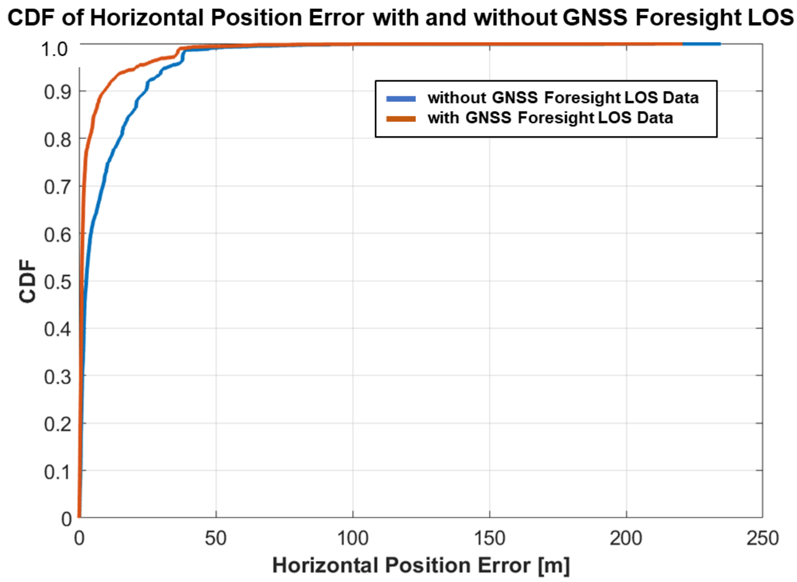

Figure 6. CDF of the horizontal position error of both solutions with and without GNSS Foresight aiding.

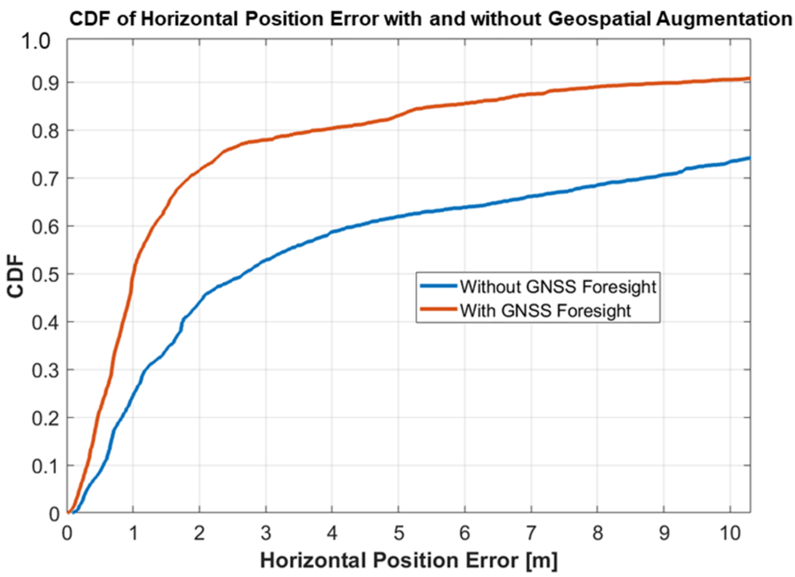

Figure 7. CDF of the horizontal position error of both solutions with and without GNSS Foresight aiding (zoomed to the 10 m position error level).

Figure 8 shows the CDF of the horizontal position error of solutions with and without GNSS Foresight aiding in a light urban environment. It can be observed that the solution with Foresight aiding still outperforms the solution without Foresight in terms of position accuracy. However, the difference in performance between the two solutions is reduced compared to what is observed in dense urban environments in Figure 6. The reason is that, in a less challenging environment where the majority of signals from satellites are LOS signals, the benefit that Foresight can provide in terms of LOS information is limited. This can also be observed in Table 3, which shows the position errors for specific percentiles, computed with and without GNSS Foresight aiding in a light urban environment.

Table 2. Position errors for specific percentiles, computed when using GNSS Foresight LOS data and when using both LOS and NLOS data, and the reduction in error determined when using GNSS Foresight LOS data (in meters and % reduction in error).

Position Solutions and Error by Percentile	25th Percentile	50th Percentile	67th Percentile	90th Percentile	95th Percentile	99th Percentile
LOS + NLOS (without GNSS Foresight aiding) [m]	1.0	2.7	7.4	24.4	32.2	47.7
LOS only (with GNSS Foresight aiding) [m]	0.6	1.0	1.6	9.3	20.7	38.2
Reduction in position error when using GNSS Foresight [m]	0.4	1.7	5.8	15.1	11.5	9.6
Reduction in position error (%) when using GNSS Foresight	42.2	62.4	77.9	62.0	35.6	20.0

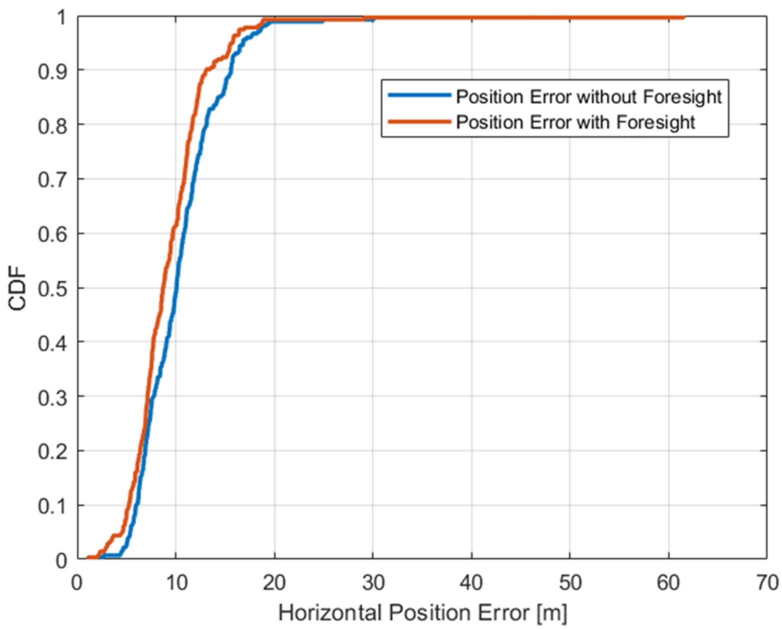

Figure 8. CDF of the horizontal position error of both solutions with and without GNSS Foresight aiding in a light urban environment.

Table 3. Position errors for specific percentiles, computed when using GNSS Foresight LOS data and when using both LOS and NLOS data, and the reduction in error determined when using GNSS Foresight LOS data (in meters and % reduction in error).

Position Solution Type and Error by Percentile	25th Percentile	50th Percentile	67th Percentile	90th Percentile	95th Percentile	99th Percentile
LOS + NLOS (without GNSS Foresight aiding) [m]	7.3	10.1	11.6	15.6	16.8	21.0
LOS only (with GNSS Foresight aiding) [m]	6.9	8.7	10.5	13.1	15.6	18.8
Reduction in position error when using GNSS Foresight [m]	0.4	1.4	1.1	2.5	1.2	2.2
Reduction in position error (%) when using GNSS Foresight data	5.4	15.6	10.6	19.5	7.7	11.4

5. Conclusions

The performance of conventional GNSS positioning in the urban environment can be degraded due to building obstructions and reflections. GNSS Foresight was developed to improve GNSS performance, integrity, and reliability in such a challenging environment by aiding the receivers with predicted LOS information. The performance of the Foresight-aided solution was evaluated by comparing it with conventional GNSS position solutions in both light and dense urban environments. The comparison results show that the Foresight aiding solution significantly reduces positioning errors and outperforms conventional GNSS positioning solutions, particularly in a dense urban environment.

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