High-accuracy GNSS Localization with Low-cost

ABM Musa
musaabm@amazon.com
Amazon
Bellevue, WA, USA

Chris Baker
bakercb@amazon.com
Amazon
Bellevue, WA, USA

Emre Eftelioglu
efteli@amazon.com
Amazon
Bellevue, WA, USA

Amber Roy Chowdhury
amberch@amazon.com
Amazon
Bellevue, WA, USA

ABSTRACT

Sub-meter accurate vehicle localization is often the ultimate goal in the automotive industry as well as fleet management today and the Global Navigation Satellite System (GNSS) is one of the most practical ways to achieve this goal. In addition to precise navigation and real-time accurate vehicle location tracking, the high-accuracy location data enables many geospatial and mapping applications. Traditionally, high-accuracy GNSS localization solutions were highly expensive. However, we can now achieve high accuracy localization by combining GNSS and Inertial Measurement Unit (IMU) along with Real-Time Kinematic (RTK) correction at a high availability with low cost. In this paper, we present the evaluation and experimental results of such a solution that we are deploying in a large vehicle fleet. Our experiments show that sub-meter localization accuracy can be achieved in most scenarios. Additionally, we present various geospatial applications of the high-accuracy GPS trajectories, some of which were previously impossible with the data collected from low-accuracy consumer-grade sensors. Finally, we share a dataset with multiple GPS trajectories containing GNSS data from both our low-cost and ground-truth GNSS systems. We believe this dataset will enable further research on various applications of high-accuracy location data as well as GNSS characteristics in different areas.

CCS CONCEPTS

• **Information systems → Global positioning systems**; **Location based services**; **Geographic information systems**.

KEYWORDS

GNSS, Location, Trajectory, Spatiotemporal

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1 INTRODUCTION

Sub-meter accurate localization is often the ultimate goal in various automotive applications and fleet management for navigational and vehicle tracking [2] purposes. In addition, high-accuracy location information has a significant impact on various geospatial applications. Until now, most of these applications were developed with low-accuracy and noisy location trajectory data obtained from smartphone GNSS or other consumer GNSS receivers, which results in either erroneous inference or complex algorithms. In contrast, high accuracy location data can significantly benefit all these applications and even enable new applications that were impossible before with low accuracy counterparts such as inferring connectivity in overlapping roads and identifying map attributes [7] like cul-de-sacs.

Recently, consumer-grade GNSS accuracy improved with D-GPS and multiple constellations (GLONASS, Galileo, BeiDou) and the accuracy can range from 5 to 10 meters under an open sky. However, GNSS accuracy can get degraded a lot in urban canyons, under tree canopies, and GNSS does not work at all indoors. To achieve sub-meter localization accuracy everywhere, we need to combine (a) carrier-phase GNSS data processing (traditional consumer GNSS receivers process code phase data), (b) Real-Time-Kinetic (RTK) correction data from base stations, and (c) Inertial Navigation System (INS) integration for GNSS-denied areas (e.g., tunnel, dense urban canyon). While all of these have multiple decades of history in the survey industry and small-scale applications, combining all of them at a large-scale is not even fully standardized in the industry yet. Additionally, these systems were very expensive costing tens of thousands of dollars in the past. Yet, in recent years, the cost of both hardware and RTK/PPP correction service has come down significantly. Therefore, by leveraging GNSS and IMU along with RTK correction, it is now possible to achieve sub-meter location accuracy with high availability at low cost.

High-accuracy localization combining GNSS, INS, and RTK correction is a complex topic. It is essential to consider multiple constellations, multiple frequencies, carrier phase processing in addition to code signal processing on the GNSS end. From the INS end, it is important to consider loosely versus tightly coupled fusion, its stability, outage duration, and error growth, which are required for precise positioning during GNSS outage (e.g., downtown, tunnels). Finally, a correction service for carrier phase processing of the GNSS signal should be added. There are a lot of variations in the correction service such as traditional RTK and more recent Precise Point Positioning (PPP), hybrid RTK-PPP [5], representation

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through State Space Representation (SSR) [4], Observation State Representation (OSR), integrity, etc. In this work, we evaluate all these together and their various trade-off to design and settle on a solution that can provide a very high accuracy location with high availability and low cost. Specifically, we use a low-cost GNSS receiver, IMU, and antenna to reduce the overall system cost. Despite being low-cost, our GNSS receiver supports all constellations, and both L1 and L5 bands, resulting in improved performance in urban canyons. We use a hybrid RTK-PPP solution, where multiple base station data are merged to create correction data over a large geographic region (e.g., USA) and only one-way communication is used to send correction data over the cloud to the GNSS receiver. This enables our solution to work in a very large geographic area with better scalability and fast convergence time. We use loosely-coupled INS integration, which is less complex, but still achieves high accuracy in GNSS denied areas.

In this paper, we present the experimental results and evaluation of our low-cost GNSS system. Our experiments show that sub-meter localization accuracy can be achieved in most scenarios (except dense downtown) and existing accuracies can be substantially improved for those challenging cases such as dense downtown areas. The primary contributions of our paper are:

- To the best of our knowledge, the first experimental study of a high-accuracy low-cost GNSS system that achieves sub-meter localization in most scenarios.
- Detail process and methods to evaluate a GNSS system for large-scale real-world deployment.
- Geospatial and mapping applications that can only be achieved from high-accuracy location trace.
- GNSS trajectory dataset to enable further research on various applications of high accuracy location data as well as GNSS characteristics in different areas.

2 EXPERIMENTAL SETUP

Figure 1 shows our experimental setup. We instrumented a vehicle with an industry-standard survey-grade GNSS reference system. The reference system provides centimeter to decimeter accuracy in almost all regions, including dense downtown areas. We consider the location data from the reference system as our ground truth. We also instrumented the vehicle with an edge computer with an integrated low-cost high-accuracy GNSS system.

This vehicle along with the reference system enables us to run controlled and repeated experiments and measure the performance of the proposed low-cost GNSS system. Note that the reference system is an expensive system costing tens of thousands of dollars. In contrast, our low-cost GNSS system costs less than a hundred dollars, making it feasible to deploy in a large-scale vehicle fleet.

Figure 2 shows our experimental route. This route is 42-mile in length and takes approximately two hours to drive. It combines dense downtown with urban canyons like Seattle, a smaller downtown like Bellevue, WA, suburban areas, and highways. Moreover, this route also has two tunnels, which are useful to test cases with complete GNSS outages.

3 EXPERIMENTAL RESULTS

The primary goal of instrumenting a vehicle with a GNSS system is to obtain very high accuracy location data. Additionally, a high-accuracy GNSS system provides other benefits such as orientation and precise timing. Here, we present the experimental results of these components.

Figure 3a shows the Cumulative Distribution Function (CDF) of location accuracy of our low-cost GNSS system for a variety of regions in a drive. Specifically, the 50th and the 90th percentile accuracy on the highway are 0.04m and 0.37m respectively. The 50th and 90th percentile accuracy in Bellevue, WA are 0.14m and 0.72m respectively. The location accuracy is very high on highways, which is expected. Despite the expectation of lower accuracy, the location accuracy was on-par for small downtown areas, i.e. Bellevue, WA, as well. This shows that low-cost GNSS systems can work well even in such downtown areas. The 50th and 90th percentile accuracy in Seattle downtown are 1.19m and 4.27m respectively, which is relatively poor compared to the highway and Bellevue. However, Seattle downtown is a very dense urban canyon and the accuracy is still significantly higher compared to the consumer-grade GNSS receivers, making our solution a better choice for different geographic varieties.

We also measured the location accuracy of a few smartphones such as iPhoneSXMax, OnePlus6, and BLU6. The iPhoneSXMax and OnePlus6 have similar location errors, and the location errors from the low-cost BLU6 are even higher. Specifically, the 50th and 90th percentile for the full route in 2 for iPhoneSXMax was 9.23m and 24.06m respectively. The 50th and 90th percentile for the full route for BLU6 were 19.33m and 70.36m respectively. This demonstrates that our low-cost GNSS system achieves orders-of-magnitude better performance compared to the typical consumer-grade GNSS in smartphones in all types of areas.

Positioning types are a good way to have confidence in location accuracy. They also provide insights into GNSS characteristics. Table 1 shows the percentage distribution of these positioning types. We have high availability (99.82%) in positioning. We achieve 85.35% RTK positioning (fixed or float), which is good. We have pure DR mode for around 10% of the time. These are tunnels, overpasses, and dense downtown areas.

The overall sub-meter accuracy enables us to achieve lane-level accuracy for GPS trajectories. Figure 4 illustrates this with an example. Lane-level accuracy is useful for mapping as it enables lane-level topology maps, turn characteristics, etc. Note that map-matching [6] is traditionally used to improve localization accuracy at the road-level. In contrast, we achieve lane-level accuracy through sub-meter GNSS localization here, which is not feasible by map-matching.

Figure 3c shows the orientation (roll-pitch-yaw) error. Orientation data itself is important for route planning for electric vehicles. Additionally, orientation data can be fused with imagery and LIDAR data, which is important for mapping applications. We have mostly sub-degree accuracy in roll and pitch. The yaw generally has a higher error. Here, the median error is 1.8 degrees, which is still highly accurate.

GNSS is the best source for high-precision timing [3]. Accurate timing is required for synchronizing data from multiple sources (e.g.

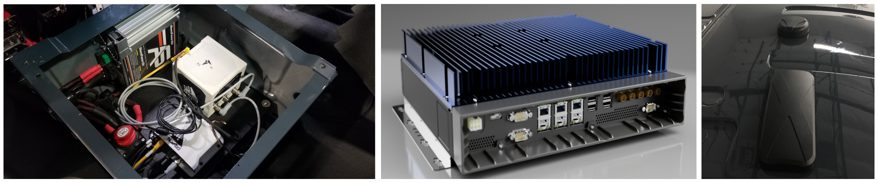


Figure 1: Experimental setup. From the left: reference ground truth system, in-vehicle computer with precision GNSS module, low-cost antenna on the roof.

Category	Explanation	Percentage
RTK-fixed	Carrier frequency is used, and integer ambiguity is resolved	57.67
RTK-float	Carrier frequency is used, but integer ambiguity is not resolved	27.68
DGPS	Only code frequency is used in differential mode	0.77
SPS	Only code frequency is used in standalone mode	4.46
DR	Only IMU-based dead-reckoning is used	9.24
Total		**99.82**

Table 1: Statistics of sign localization.

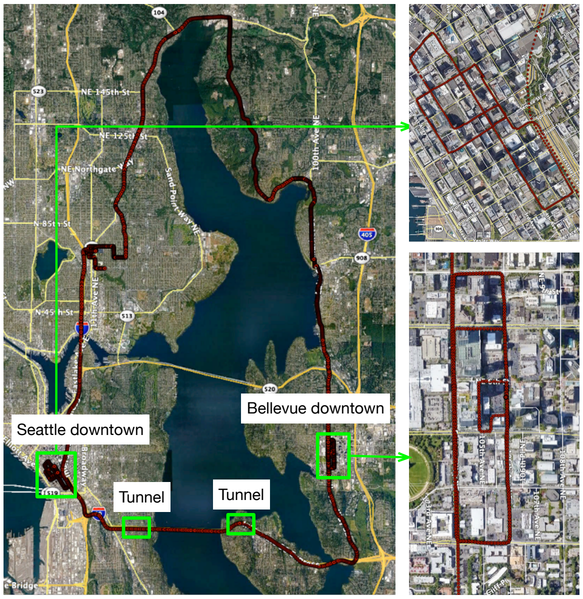


Figure 2: Experimental route.

GNSS, IMU, Camera, etc.). Our GNSS system outputs a Pulse-Per-Second (PPS) signal, which enables us to achieve timing accuracy of a few microseconds. Additionally, inaccurate timing can result in inaccurate locations. We observed that smartphones and low-cost consumer-grade GNSS receivers encounter this type of error.

4 APPLICATIONS OF HIGH ACCURACY LOCATION DATA

High-accuracy GPS trajectories are very useful for a variety of mapping and geospatial applications. By using high accuracy location data, some applications either get a significant accuracy boost or can reduce algorithm complexity by doing less processing on the trajectory data. Furthermore, it enables new applications that would have been impossible with low-accuracy counterparts. In this section, we discuss some applications like these.

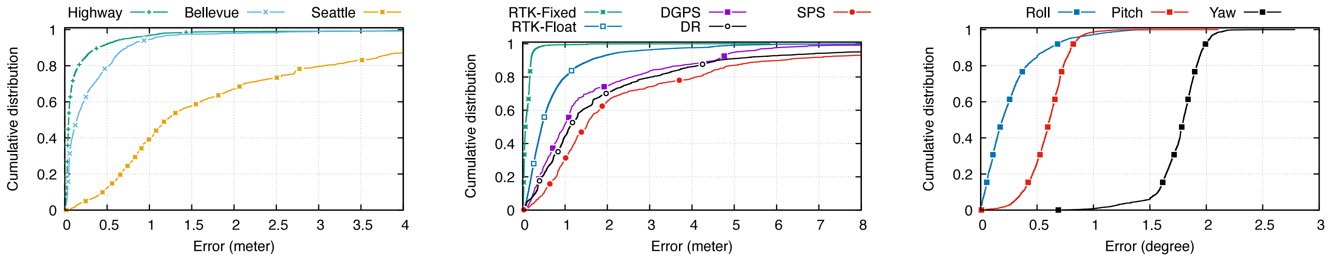
4.1 Map construction

Map construction [1] is one of the primary applications of GPS trajectories. Figure 5a shows a comparison of the low-accuracy GPS trajectories collected from smartphones and our high-accuracy GPS trajectory collected from a vehicle. The example here shows the substantial difference between these and indicates that such high accuracy GPS trajectories can enable better map inference approaches that are not going to be dependent on satellite images.

4.2 Road network connectivity and separation

Overhead bridges such as the example shown in Figure 5b are hard to distinguish using the existing low-accuracy GNSS location trajectories. Considering the ever-increasing complexity of road networks, it becomes hard to provide accurate connectivity between these. In the example, it can be seen that such complex road topologies can be recovered using the high-accuracy GNSS data with their altitude information. Despite they are often overlooked, these use cases can reduce the manual connectivity refinement tasks, which are labor intensive and error-prone, substantially for road inference frameworks. Moreover, it will bring us one step closer to automated map updates without human intervention.

We obtain very high accuracy speed data as well from our high-accuracy GPS trajectories. Figure 5c shows a sample high-accuracy GPS trajectory color-coded by vehicle speed. It clearly shows that we can automatically obtain the speed profile of various adjacent roads that can have drastically different speed limits. Moreover, identification of occasional slow-downs on various road segments can provide valuable insights for transportation officials who would work on the structural quality (bumps, cracks, etc.) of the road networks.



(a) Location error for various regions. **(b) CDF of location error for various positioning types.** **(c) Orientation error.**

Figure 3: GNSS error

Figure 4: Lane-level localization

(a) Map construction. **(b) Road connectivity.** **(c) Speed Profile.** **(d) Cul-de-sacs identification**

Figure 5: Applications

4.3 Map attributes

Road inference frameworks in literature are usually focused on inferring the topologies of those road segments. However, there are interesting yet complicated attributes that can be useful for further analysis. For example, Figure 5d shows an example with cul-de-sacs. Despite the lack of their definition on road networks, such attributes are important to make decisions about the possibility of making u-turns, especially with larger vehicles.

5 DATASET

We share a detailed dataset combining both our low-cost GNSS system and our ground truth reference GNSS system here: https://github.com/amazon-research/precision-gnss.

6 CONCLUSION

In conclusion, we present the evaluation and experimental data from low-cost high-accuracy GNSS systems as well as illustrations of applications that can leverage such data.

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