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Kinematic Precise Point Positioning Performance-Based Cost-Effective Robot Localization System

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Abstract: The use of high-precision positioning systems in modern navigation applications is crucial since location data is one of the most important pieces of information in Industry 4.0, especially for robots operating outdoors. In the modernization process of global navigation satellite system (GNSS) positioning, precise point positioning (PPP) has demonstrated its effectiveness in comparison to traditional differential positioning methods over the past thirty years. However, various challenges hinder the integration of PPP techniques into Internet of Things (IoT) systems for robot localization, with accuracy being a primary concern. This accuracy is impacted by factors such as satellite availability and signal disruptions in outdoor environments, resulting in less precise determination of satellite observations. Effectively addressing various GNSS errors is crucial when collecting PPP observations. The paper investigates the trade-off between kinematic PPP accuracy and cost effectiveness, through the examination of various influencing factors, including the choice of GNSS system (single or mixed), observation type (single or dual frequency), and satellite geometry. This research investigates kinematic PPP accuracy variation on a 10.4 km observed track based on different factors, using the GNSS system (single or mixed), and observation type (single or dual frequency). It can be concluded that mixed (GPS/GLONASS) dual frequency offers a 3D position accuracy of 9 cm, while mixed single frequency offers a 3D position accuracy of 13 cm. In industry, the results enable manufacturers to select suitable robot localization solutions according to the outdoor working environment (number of available satellites), economical constraint (single or dual frequency), and 3D position accuracy.

Keywords: mobile robots; kinematic PPP; localization; GPS/GLONASS; single/dual frequency

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1. Introduction

A robot's localization is the problem of estimating the robot's position relative to its environment from sensor observations. Localization is a necessity for successful mobile robot systems; it is the most fundamental problem in providing a mobile robot with autonomous capabilities [1]. The robot must maintain an accurate knowledge of its position and orientation to achieve autonomous navigation [2]. Many techniques are used for robot localization such as visual-based localization (the use of cameras on the robot to detect and recognize landmarks in the environment [3]; these landmarks are then used to estimate the robot's position), simultaneous localization and mapping (SLAM) (enables a robot to create a map of an unknown environment while simultaneously determining its position within the map) [4,5], radio frequency identification (where tags can be placed in the environment, and the robot can detect these tags and use them to determine its position), inertial-based localization (inertial sensors like accelerometers and gyroscopes can be used to track the robot's motion and estimate its position and orientation), long-term evolution (LTE) and wheel odometry-based localization (in the case of GPS-denied outdoor environments, LTE filter and the mobile robot position is estimated given the applied changes in odometry and received LTE [6]. However, the root-mean-square error (RMSE) of the position accuracy results is 13.07 m, and GPS-based localization (GPS can be used for indoor [7] or outdoor robot localization [8–13] by providing the robot's position relative to the global coordinate system). GPS-based localization is considered more cost effective compared with other techniques [12,14,15]. GPS is a satellite-based global positioning system that started with the USA system (GPS) (1991) and evolved into four global systems: USA (GPS), Russia (GLONASS), China (BeiDou), and Europe (Galileo). Those GNSSs offer a greater number of visible satellites with better distribution and more civilian signals that ensure better accuracy for robot localization. GPS-based localization is ideal for outdoor environments and not suitable for indoor environments because of the lack of satellite signals. However, integration of GPS/INS systems could be used to account for satellite outage intervals [14,16–18].

GNSSs are satellite-based systems for measuring position and time on Earth. The accuracy of the estimated position depends mainly on the number of employed satellites. The issue of an accurate, reliable, and secure GNSS-based localization and navigation approach for mobile robotics has been widely addressed by several research and industrial projects, and numerous solutions have been developed. GPS and GLONASS are the two GNSSs that are currently accessible and commonly used in mobile robotics for robot localization. The Galileo and BeiDou systems are emerging GNSSs for mobile robot applications. Additional sensors and/or filter-based systems can be combined with GNSS to enhance position accuracy [19,20], such as Galileo E5 AltBOC with inertial measurement sensors [21], the real-time kinematics differential global position system (RTK-DGPS) with a laser range finder [22], and the low-cost RTK-GPS [23,24] (position accuracy of 0.08 m–0.1 m). Melita et al. confirmed the performance of GNSS and satellite/ground-based augmentation systems for the autonomous lawn mower's localization and navigation [25]. The assessment was performed based on a comparison of the proposed localization algorithm with the traditional differential GPS positioning system. The satellite/ground-based augmentation systems-based localization solution presents technical barriers for a lot of potential customers due to the lack of global coverage of augmentation systems. Zhang et al. developed a new path-planning algorithm for unmanned aerial vehicles reducing the potential GPS positioning error due to obstacles [26]. The mean real compiled positioning error is reduced from 17.52 m to 4.94 m. Zhang et al. investigated the enhancement of positioning accuracy using GNSS collaborative positioning receivers in urban regions [27].

GNSS users have considered differential positioning the sole accurate positioning technique for many decades. Differential positioning provides the highest accuracy with many limitations. The limitations primarily involve the requirement for a reference station with known coordinates, restrictions on the distance between the rover and the reference station, and the necessity for simultaneous observations between the reference and rover stations.

PPP is a cost-effective standalone positioning technique, requiring a single GNSS receiver. PPP uses un-differenced, differenced single-frequency, and differenced dual-frequency pseudo-range and carrier-phase observations along with precise satellite orbit and clock products to produce decimeter-to-sub-centimeter positioning in real-time and post-processing [28–33]. PPP is considered a strong alternative for differential positioning as it provides an accuracy that matches the need for enormous static and kinematic applications. PPP requires only one receiver to collect observations at an unknown station, while the differential technique requires two receivers to gather observations simultaneously, one at a known position station and the other at an unknown station.

Robot localization using the GNSS-PPP technique is considered a promising cost-effective tool compared with other techniques that need more investigation from researchers [34,35]. The GNSS-PPP technique can be used for real-time robot localization applications [17,36]. This technique enables the design of cyber-physical system (CPS)-based mobile robots according to RAMI 4.0 [37,38]. An architecture of CPS-based mobile robots for localization purposes is proposed in Figure 1. The choice of an architectural design comprising five layers (physical, sensing, network, and control) draws an analogy with the successful and efficient modeling and implementation of CPS in CNC machine tools [39]. GSM and GNSS (GPS/GLONASS) receiver modules have become increasingly affordable. The implementation of an Arduino unit including GPS and GSM modules, along with a basic Arduino board, costs approximately USD 125 for a single frequency. Typically, single GNSS-based module (GPS or GLONASS) devices supporting dual-frequency functionality are relatively more expensive (about 82%) than single-frequency ones. A multi-GNSS Arduino unit with a dual frequency typically costs around 76% more than a single-GNSS unit. Notably, prices may also vary based on the brand and optional features of the devices. The widespread adoption of this architecture for mobile robot localization based on an online IoT system in industrial applications has faced setbacks due to constraints on position accuracy [40].

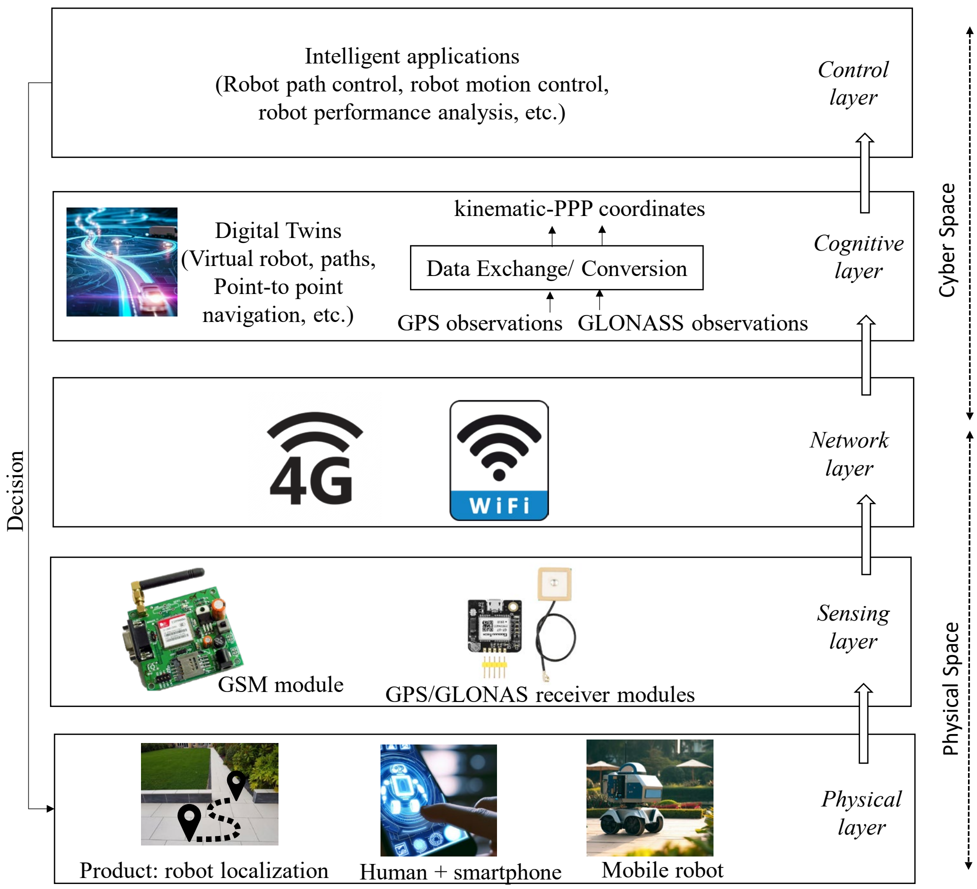

Figure 1. The architecture of CPS-based mobile robots for localization function.

Researchers have continued their efforts for more than two decades to increase the accuracy provided by PPP. PPP accuracy depends mainly on the used GNSS systems (single or mixed), observation type (single or dual), duration of observations, satellite geometry, and processing software capabilities [41–47]. Kinematic PPP could be used for different applications in strategic fields such as transport, mobile robots, infrastructure, hydrography, and precision agriculture. Also, it is useful in areas where the GNSS infrastructure is not completely developed [48].

Kinematic PPP is considered a hot topic for research, and there is a great research effort dedicated to improving the accuracy of kinematic PPP. Many researchers proved that kinematic PPP provides less accuracy than static PPP because of limitations in collected observations for each station. Static PPP could involve hundreds of collected observations at each station [33], while kinematic PPP deals only with one observation at each station.

So, extra research effort is needed to improve the accuracy of kinematic PPP based on factors such as used systems (single or mixed), observation type (single or dual frequency, and satellite geometry.

Marreiros et al. explored the application of PPP solutions in marine applications, reporting a decimeter-level accuracy in ellipsoidal height comparisons [49]. Similarly, the PPP solution for maritime applications was evaluated by Alkan et al. [50]. At Halic Bay, Istanbul, Turkey, in August 2009, a test was conducted. Leica Geo-Office 8.0 software was used to acquire the reference differential GNSS (DGNSS) solution, and the Canadian Spatial Reference System (CSRS) PPP online service was used to generate the kinematic PPP solution. The kinematic PPP solution provided a position accuracy of 15 cm and height accuracy of up to 25 cm, compared to the DGNSS solution. Abdallah et al. investigated the accuracy of the kinematic PPP solution using Bernese GNSS Version 5.2 software for hydrographic applications [51]. Their PPP solutions were compared with the double-difference solution from Bernese software. The research involved two kinematic trajectories along the Rhine River in Duisburg, Germany. In the first kinematic trajectory, the kinematic PPP solution exhibited standard deviations of 6 cm in the east, 2.1 cm in the north, and 6.8 cm in height. The second trajectory, which started with 40 min of quasi-static observation time (non-moving vessel), achieves a more precise solution. The standard deviation values of all measurements are 1.7 cm in the east, 2.6 cm in the north, and 4.9 cm in height. Ju et al. assessed the effectiveness of GNSS kinematic PPP and PPP-Inter Ambiguity Resolution (IAR) techniques in monitoring the structural health of bridges [52]. This investigation utilized regional network stations located in China. The findings indicated that both GNSS kinematic PPP and PPP-IAR approaches can achieve precise structural health monitoring of bridges, while PPP-IAR is anticipated to exhibit quicker convergence and greater real-time monitoring accuracy. Gurturk et al. presented the possibility of using the PPP-Ambiguity Resolution (AR) method in the precise positioning of the aircraft [53]. GPS data were gathered during two distinct photogrammetric flights conducted within a project aimed at creating a digital photogrammetric map of the Izmir region in Turkey. Accuracies of 2.75 cm, 3.0 cm, and 6.0 cm were achieved for north, east, and height, respectively.

Recently, there has been a notable trend towards increased accessibility and affordability of single and dual frequencies, along with the availability of GPS and GLONASS satellites. This development holds great promise for facilitating a more flexible integration of mobile robot localization in industrial applications through online IoT systems. However, to ensure that these advancements align with the precision accuracy required by mobile robots, further investigations and research are necessary. These studies will help determine the suitability of these technologies for meeting the specific requirements of outdoor mobile robots in the context of Industry 4.0 [5,40].

This paper addresses the accuracy issue of robot localization systems using the GNSS-PPP kinematic technique. A GPS, GLONASS, and multi-GNSS with single- and dual-frequency observations-based kinematic PPP solutions are proposed. The six solutions aim to provide robot designers with balanced alternatives between accuracy and cost.

The rest of the paper is organized as follows: In Section 2, the scope of the study is presented. The results of the six studied solutions are shown and evaluated in Section 3, followed by Section 4. The conclusion is presented at the end.

2. Test Study Scope

The scope of the study is to investigate the variation in kinematic PPP's accuracy based on the used system (GPS, GLONASS, and mixed GPS/GLONASS). Also, the study investigates the effect of using single- and dual-frequency observations from those three system configurations on kinematic PPP's accuracy (Figure 2). Commonly, the use of a single-frequency receiver is more cost-effective than a dual-frequency receiver.

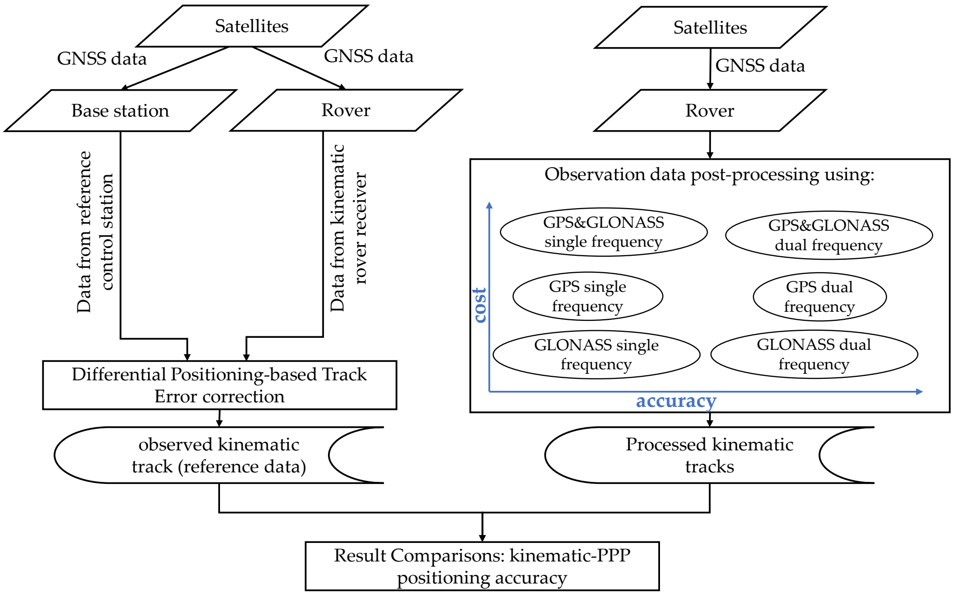

Figure 2. Study scope.

A kinematic track of 10.4 km was observed on the campus of King Saud University [54], Riyadh, KSA (Figures 3 and 4) using dual-frequency mixed (GPS/GLONASS) observations using the Sokkia-GRX1 instrument [55]. Observations were gathered using a 15-degree mask elevation angle and a one-second observation interval in clear sky conditions to prevent multipath errors. The rover receiver was mounted on a moving vehicle with an average speed of 15 km/h, and its antenna was positioned vertically above the vehicle's roof for an unobstructed sky view. The total observation time was 54 min and 29 s. The Sokkia-GRX1 instrument processed multiple signal types, including GPS (L1, L2, C/A) and GLONASS (L1, L2, C/A) signals. Observation timing was carefully planned to maximize the number of visible satellites and achieve the best position dilution of precision (PDOP) values. Table 1 presents the no. of visible satellites and PDOP values for used systems on observation day (22,306 GPS day).

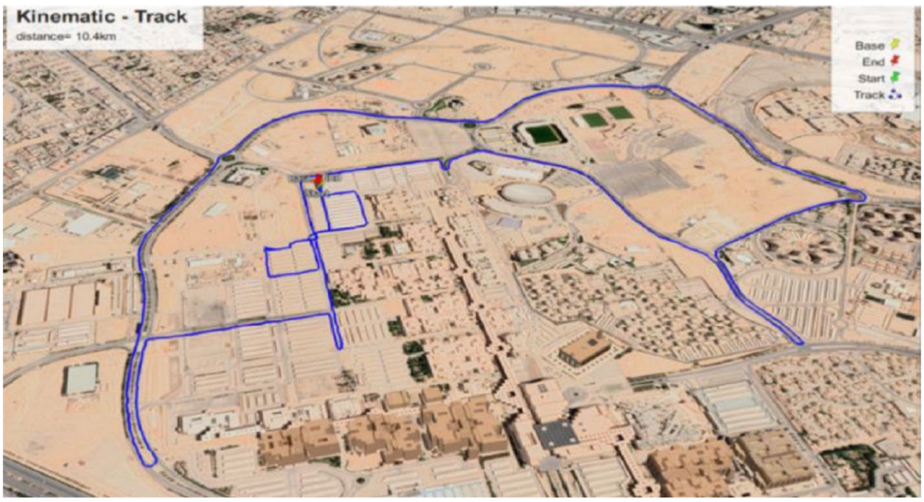

Figure 3. The study's observed kinematic track (KSU campus), Riyadh, KSA (8 October 2022).

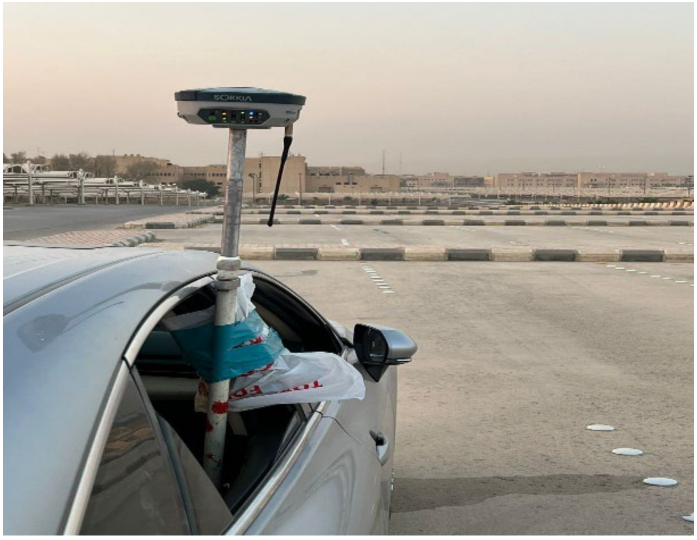

Figure 4. The rover setup for the study's observed track (KSU campus), Riyadh, KSA (8 October 2022).

Table 1. Average (no. visible satellites and PDOP) for observed track during GPS day (22,306).

System	Average No. Visible Satellites	Average PDOP
GPS	9	1.85
GLONASS	6	3.41
Mixed GPS/GLONASS	15	1.39

The reference solution was acquired through differential positioning, utilizing a reference station with a maximum baseline of 3 km. This differential solution was generated by processing two observation files (Figure 2), one from the reference control station and the other from the kinematic rover receiver. Differential corrections from the reference station are used to correct errors in the observations of the kinematic rover receiver. Six PPP solutions were investigated using NET_DIFF online Processing service [56], namely GPS (single and dual frequency), GLONASS (single and dual frequency), and mixed GPS/GLONASS (single and dual frequency). TEQC software (2019 Feb 25 final release) was used during this study for translation, editing, and quality checks of the originally collected observation file [57]. The translation process aims at converting the format of the originally collected observation file from binary to Rinex format (required by the online processing service). The editing process aims to generate six observation files from the originally collected observation file. Each generated file provides a unique PPP solution (GPS dual frequency, GPS single frequency, GLONASS dual frequency, GLONASS single frequency, mixed GPS/GLONASS dual frequency, and mixed GPS/GLONASS single frequency).

The observation data were processed using Net_Diff 1.16 software for GNSS download, positioning, and analysis [56]. The Net_Diff service allowed us to carrying out SPP/PPP/PPP-AR/DSPP/DPPP/RTK/PPP-RTK [1,58]. From single frequency to triple frequency, all the current GPS, GLONASS, BeiDou, Galileo, QZSS, and IRNSS signals are enabled.

Table 2 presents PPP processing parameters used in Net_Diff. software. The advantages of Net_Diff. service over other PPP services is its ability to process observations from all available systems (GPS/GLONASS/BeiDou/Galileo/QZSS/IRNSS) with different combinations between those systems as well as its ability to process different-frequency observations (single/dual/triple). Those two advantages are ideal for research purposes.

Table 2. PPP processing parameters used in Net_Diff. service.

PPP Processing Parameters	Values
Reference System	ITRF2008
Coordinate format	ENH (UTM)
Satellite orbit and clock ephemeris source	CODE final 30 s for clock 15 min for orbits
Satellite phase center offset	IGS ANTEX
Receiver phase center offset	IGS ANTEX
Tropospheric model	Saastamoinen
Meteorological model	GPT
Mapping function	Global Mapping Function (GMF)
Ionospheric model	Final Global Ionospheric Maps (GIM) from IGS
Mask angle	10°
Observation type	Code + Phase
System	GPS/GLONASS/BeiDou/Galileo/QZSS/IRNSS
Frequency	Single/Dual/Triple
Processing mode	Static
Estimation method	Kalman Filter

3. Study Results

3.1. Kinematic PPP Positioning Accuracy Using Single-Frequency Observations

The study of kinematic PPP accuracy using single-frequency observations is crucial for robot localization systems as it provides a low-cost solution compared with the high-cost solution using dual-frequency observations [30]. The results of this study show that kinematic PPP positioning accuracy is computed relative to the reference differential solution. Figure 5a presents kinematic PPP coordinate differences using GPS single-frequency observations. Figure 5b presents kinematic PPP coordinate differences using GLONASS single-frequency observations. Figure 5c presents kinematic PPP coordinate differences using mixed GPS/GLONASS single-frequency observations.

3.2. Kinematic PPP Positioning Accuracy Using Dual-Frequency Observations

The study of kinematic PPP accuracy using dual-frequency observations is crucial for robot localization systems as it provides the ideal solution compared with the less accurate solution using single-frequency observations. Dual-frequency observations mitigate efficiently the Ionospheric delay (the largest source of errors for GNSS observations) compared with single-frequency observations. Figure 5d presents kinematic PPP coordinate differences using GPS dual-frequency observations. Figure 5e presents kinematic PPP coordinate differences using GLONASS dual-frequency observations. Figure 5f presents kinematic PPP coordinate differences using mixed GPS/GLONASS dual-frequency observations.

As a result of this study, kinematic PPP positioning accuracy is computed by comparing kinematic PPP observation with the reference differential solution.

Figure 6a presents kinematic PPP RMSE using single-frequency observations from GPS, GLONASS, and mixed GPS/GLONASS.

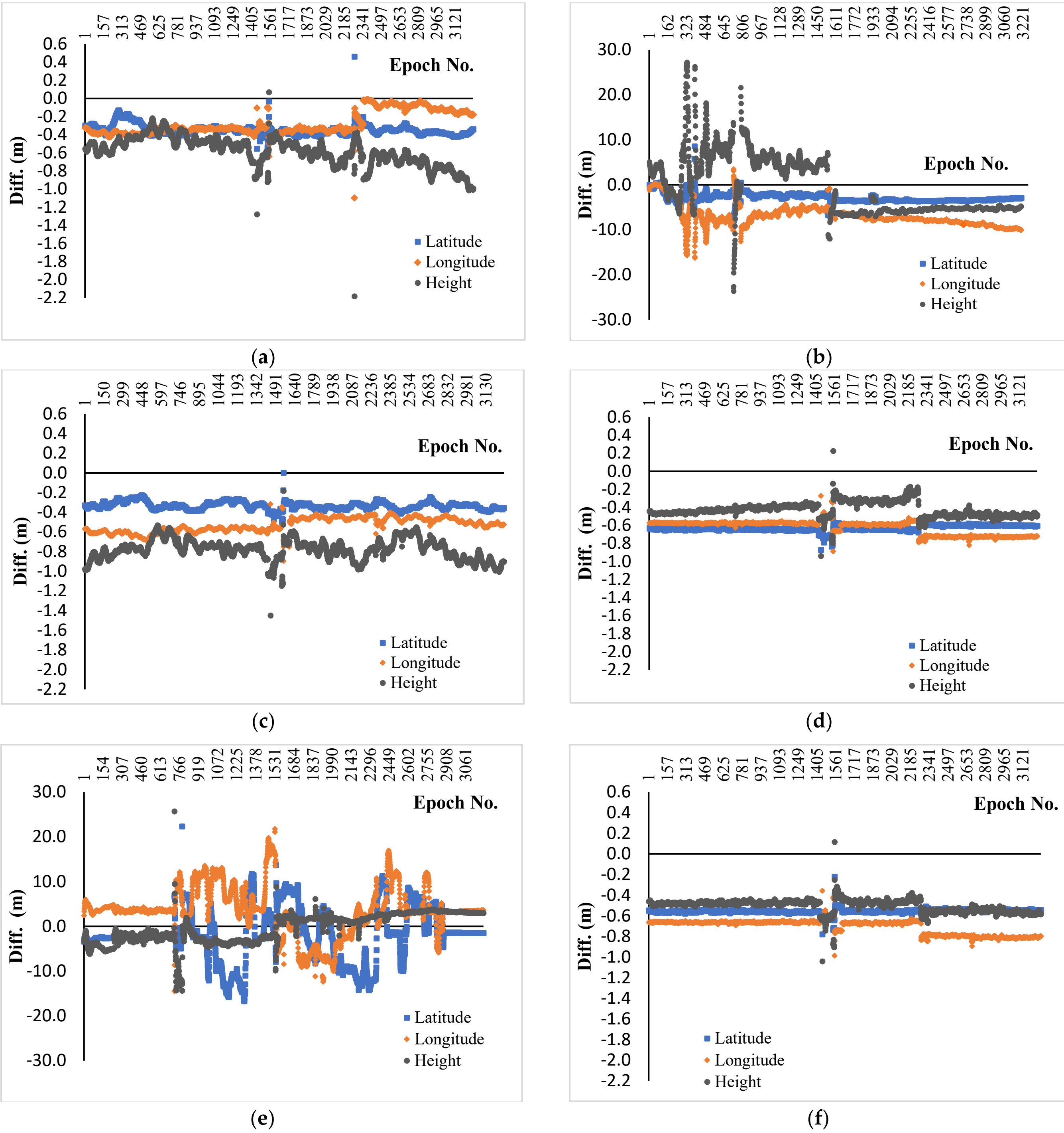

Figure 5. Kinematic PPP coordinate differences using (**a**) GPS single-frequency observations, (**b**) GLONASS single-frequency observations, (**c**) mixed GPS/GLONASS single-frequency observations, (**d**) GPS dual-frequency observations, (**e**) GLONASS dual-frequency observations, and (**f**) mixed GPS/GLONASS dual-frequency observations.

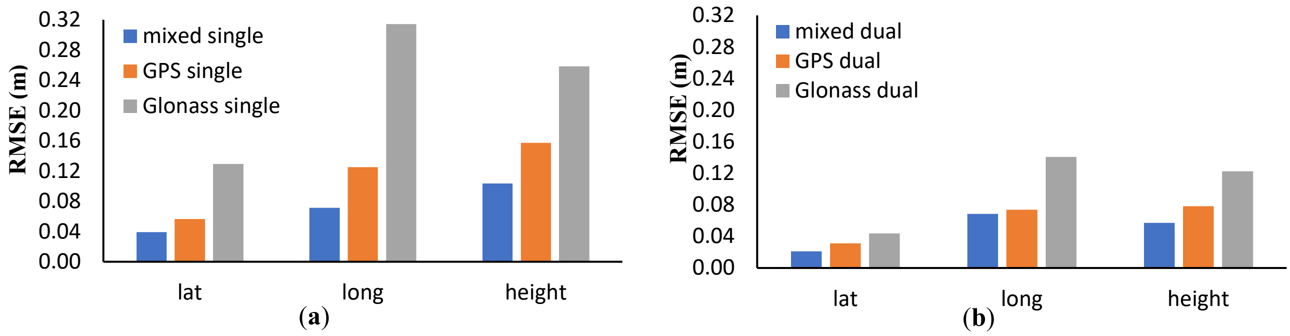

Figure 6. Kinematic PPP RMSE from GPS, GLONASS, and mixed GPS/GLONASS using (**a**) single-frequency observations, and (**b**) dual-frequency observations.

Figure 6b describes kinematic PPP RMSE using dual-frequency observations from GPS, GLONASS, and mixed GPS/GLONASS.

4. Discussion

Table 3 presents the RMSE and 3D position RMSE for different kinematic PPP solutions resulting from this study compared with the differential solution.

Table 3. RMSE from different kinematic PPP solutions compared with the differential solution.

Obs. Type	System	RMSE (m) Lat.	Long.	Height	3D Position RMSE (m)
Single Frequency	GPS	0.056	0.125	0.157	0.208
	GLONASS	0.129	0.314	0.258	0.426
	GPS/GLONASS	0.039	0.071	0.104	0.132
Dual Frequency	GPS	0.031	0.074	0.078	0.112
	GLONASS	0.044	0.141	0.122	0.192
	GPS/GLONASS	0.021	0.069	0.057	0.092

On the date of the study (22,306 GPS day), GPS has 31 healthy satellites, while GLONASS has 22 healthy satellites. This constellation status explains the GPS no. of visible satellites (nine), while the GLONASS no. of visible satellites was only six. The mixed system offers 15 visible satellites with 1.68 position (3D) dilution of precision (PDOP). Mixed PDOP improved by 25% over GPS-PDOP and by 100% over GLONASS-PDOP. As GPS is better than GLONASS in satellite geometry for the study geographic region (Riyadh, KSA), it can be concluded that GPS will provide better performance for kinematic PPP positioning accuracy over GLONASS. However, the GLONASS system serves as a viable alternative to GPS, and also, it can augment GPS in different environments to ensure better behavior using a mixed system (GPS/GLONASS).

From the resulting kinematic PPP coordinate differences shown in Figure 5a,b,d,e, it can be concluded that GPS offers stable performance for kinematic PPP positioning accuracy. As GLONASS's performance is variable due to the effect of satellite geometry variation, PDOP gets higher, which indicates worse positioning accuracy. GPS single frequency performance is twice as great as GLONASS single frequency. The GPS dual frequency performance is twice as good as the GPS single frequency. The accuracy difference can be justified due to the excellent performance of dual frequency observations in mitigating the ionospheric delay which considers the largest source of error that affects GNSS observations. GPS and GLONASS provide better positioning accuracy for latitude than longitude coordinates using either type of observation (single or dual). This behavior is due to the increased number of satellite tracks in the latitude direction (north–south) compared with the least number of satellite tracks in the longitude direction (east–west).

From Figure 5c,f and Table 3, it can be concluded that a mixed system (GPS/GLONASS) is providing the best performance in positioning accuracy compared with individual systems (GPS or GLONASS). Using mixed single-frequency observations improves the acquired accuracy by 100% over GLONASS and by 38% over GPS.

Using mixed-dual frequency observations improves the acquired accuracy by 100% over GLONASS and by 18% over GPS. Using mixed-dual frequency observations improves the acquired accuracy by 30% over mixed single-frequency observations. The results of Table 3 are in agreement with recent studies [33,35,53,59]. The paper's findings on accuracy and cost percentages provide valuable design guidelines for mobile robot designers, expediting the sustainable integration of outdoor robot-based CPS systems in Industry 4.0.

5. Conclusions

Improving kinematic PPP positioning accuracy needs further research efforts, given its significance in serving various strategic applications aligned with sustainability goals and the broader vision of KSA and global requirements. GNSS-PPP is a promising cost-effective technique for robot localization. The study proves the effect of the number of working satellites offered by each system over the acquired positioning accuracy. GPS systems currently provide a greater number of working satellites (31) compared with the GLONASS system (22). GPS provides better kinematic PPP accuracy over GLONASS. The study presents ideal kinematic PPP solutions using dual-frequency observations as well as cost-effective kinematic PPP solutions using single-frequency observations. GPS dual frequency offers accuracies of (0.03 m, 0.07 m, and 0.08 m) for latitude, longitude, and height, respectively, with 3D position accuracy of 11 cm, while GPS single frequency offers accuracies of (0.06 m, 0.13 m, and 0.16 m) for latitude, longitude, and height, respectively, with 3D position accuracy of 21 cm. GLONASS dual frequency offers accuracies of (0.04 m, 0.14 m, and 0.12 m) for latitude, longitude, and height, respectively, with 3D position accuracy of 19 cm, while GLONASS single frequency offers accuracies of (0.13 m, 0.31 m, and 0.26 m) for latitude, longitude, and height, respectively, with 3D position accuracy of 43 cm. Mixed (GPS/GLONASS) dual frequency offers accuracies of (0.02 m, 0.07 m, and 0.06 m) for latitude, longitude, and height, respectively, with 3D position accuracy of 9 cm, while mixed single frequency offers accuracies of (0.04 m, 0.07 m, and 0.10 m) for latitude, longitude, and height, respectively, with 3D position accuracy of 13 cm. The paper's findings provide reliable alternative solutions for robot localization, considering the availability of satellites in outdoor environments, the economic aspect of using single or dual frequency, and the required level of position accuracy. Further research is needed to enhance kinematic PPP accuracy by incorporating GALILEO and BeiDou alongside GPS and GLONASS in multi-GNSS observations. Using the four global systems will ensure a greater number of visible satellites, better PDOP, and an increased amount of collected observations which will reflect better achieved kinematic PPP accuracy that meets the desired accuracies for a robot localization system. The achieved kinematic PPP accuracies will empower the advancement of real-time robot localization applications. GNSS technology offers a low-cost alternative for robots operating outdoors.

Author Contributions: All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by A.F. The first draft of the manuscript was written by A.F. and M.T. All authors discussed and approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

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