



Enhancing the Quality of Kinematic PPP in Partially and Heavily Obscured-Sky Using Stand-Alone Double Differencing Carrier Phase Relative Positioning

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Abstract

Kinematic Precise Point Positioning (PPP) provides high-accuracy absolute positioning but suffers from performance degradation and solution outages in partially and heavily obscured GNSS environments due to satellite blockage, cycle slips, and ambiguity reconvergence. This study proposes a loosely coupled integration of Stand-Alone Double-Differenced Carrier Phase (SADDCP) relative positioning with raw kinematic PPP using forward and reverse Kalman filtering to enhance solution continuity and reliability. In the proposed scheme, precise 3D relative positioning from SADDCP, when at least three healthy satellites are available, is used to bridge PPP solution gaps caused by fewer than five satellites or during ambiguity reconvergence. When only two satellites are available, a planar (2D) solution is maintained until full PPP restoration. Experimental validation was conducted along a pre-surveyed trajectory spanning open-sky, partially obscured, and heavily obstructed urban environments. In open-sky conditions, raw PPP achieved 3–5 cm accuracy in all components with 100% 3D continuity, while the integrated solution showed comparable performance with slight improvement, particularly in height. In partially obscured environments, integration improved PPP accuracy by approximately 0.7 m, 0.9 m, and 1.15 m in the E, N, and H components, respectively, while maintaining 100% continuity. In heavily obscured areas, raw PPP covered only 21% of the trajectory with accuracy of 2.64, 3.26, 5.37 m in E, N & H components, respectively, whereas the integrated solution achieved 65% (2D) and 89% (3D) continuity with accuracies of about 1.3 m in plan and 1.7 m in height. The results demonstrate that SADDCP/PPP integration significantly enhances positioning continuity and accuracy in challenging GNSS environments. Future work will investigate further integration with MEMS-based INS to mitigate solution outages and cumulative drift in severely obstructed conditions.

Keywords: PPP; Single frequency; Double differencing; Kalman filter; Relative positioning; Multipath; Partially and heavily obscured sky

1. Introduction

Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS) and Russia's Global Navigation Satellite System (GLONASS), are satellite-based navigation and positioning systems that enable the determination of instantaneous position and velocity using passive range measurements [1]. GNSS operate continuously under all weather conditions and provide high-accuracy, real-time positioning and timing information on a global scale [2]. These systems rely on constellations of satellites transmitting signals on two primary frequencies, each modulated with Coarse/Acquisition (C/A) and Precise (P) codes [3]. The transmitted signals allow GNSS receivers to derive pseudo-range and carrier-phase observations, which form the foundation of modern navigation and geodetic surveying applications [4]. The GNSS pseudo-range between a receiver and a satellite is obtained by correlating the satellite code with the internally generated receiver code and scaling the measured time difference by the speed of light [5]. Carrier-phase observations are formed by removing the code modulation from the received signal. Carrier phase measurements can reach a precision of approximately 0.01 cycles, corresponding to millimeter-level accuracy. However, only the

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fractional phase and the accumulated integer number of wavelengths can be measured while the satellite to receiver link remains continuous. The initial total number of integer wavelengths is unknown, making absolute single epoch positioning impossible using carrier phase observations alone. This unknown quantity is referred to as the integer ambiguity [6].

Differential GNSS (DGNSS) techniques can be used to resolve this issue by enabling precise relative positioning. Relative positioning aims to determine the coordinates of an unknown point with respect to a known reference point, or equivalently, to estimate the vector (baseline) between two points, which requires simultaneous observations at both locations [7]. In DGNSS, several error sources are reduced or eliminated due to their high spatial correlation over short baselines. Dual-frequency DGNSS configurations can achieve millimeter-level accuracy, whereas single-frequency systems typically provide decimeter-level precision at significantly lower cost [8]. Despite its high accuracy, DGNSS requires proximity to a reference station, limiting its applicability on a global scale. Differenced observations can be formed from either code or carrier-phase measurements and may take the form of single, double, or triple differences [9]. Single differences can be computed between two receivers, two satellites, or two epochs. Double differences are obtained by differencing two single differences, while triple differences involve all three forms: two receivers, two satellites, and two epochs [10].

Stand-Alone Double Differences Carrier Phase (SADDCP) is a differencing approach that combines two single differences across satellites and epochs using observations from a single receiver. In this technique, single-frequency carrier-phase observations are first difference between consecutive epochs and then difference between satellites [6,7]. These operations eliminate the integer ambiguity as long as continuous tracking between the satellite and receiver is maintained. Furthermore, SADDCP removes receiver clock errors, reduces satellite clock errors due to clock stability over short transmission intervals, mitigates satellite orbit errors, and reduces ionospheric and tropospheric delays to their temporal variations. Multipath errors remain but can be reduced due to their temporal correlation, while receiver measurement noise is amplified. SADDCP is therefore considered an accurate velocity estimation technique based on single-frequency stand-alone GPS observables. Precise relative positioning can subsequently be achieved by integrating the estimated velocity over time [8].

In contrast to carrier-phase differential techniques, Precise Point Positioning (PPP) provides a globally applicable, absolute positioning solution that does not rely on local reference stations [11]. PPP utilizes precise satellite orbit and clock products, typically provided by the International GNSS Service (IGS), along with comprehensive models accounting for atmospheric and relativistic effects [12]. PPP can achieve centimeter-level accuracy in both static and kinematic modes, although it generally requires longer convergence times than DGNSS [13]. The quality of GNSS positioning techniques, including stand-alone code, differential code and carrier-phase, and PPP, is influenced by several factors, including satellite geometry, atmospheric propagation delays [14], and receiver quality [15]. Code-based positioning typically achieves meter-level accuracy, which is sufficient for low-precision applications such as vehicle navigation [16], drone operations [17], and the generation of low-accuracy Ortho-mosaic images and digital elevation models [18]. High-precision applications, such as geodetic control, deformation monitoring, and precision engineering, require centimeter-level accuracy, which can be achieved using advanced techniques such as DGNSS and PPP [19,20]. For SADDCP, relative positioning accuracy under open-sky conditions can reach the millimeter level between consecutive epochs and remain below 5 cm in multipath-affected environments. However, SADDCP errors are cumulative over time, necessitating periodic corrections from an absolute positioning source [6].

Multipath is one of the major GNSS error sources in urban environments, where reflected signals are received instead of direct signals, increasing the apparent satellite to receiver distance. Severe multipath conditions may lead to signal loss, and if the number of healthy tracked satellites drops below five, the PPP solution may be lost. Although satellite re-acquisition is typically rapid with modern multi-channel receivers, ambiguity resolution may require a significant convergence period, during which the PPP solution may be unavailable or degraded. In contrast, SADDCP requires only three healthy satellites tracked over two consecutive epochs to determine three-dimensional (3D) relative positioning. When fewer than three satellites are available, two-dimensional (2D) plane relative positioning can still be achieved.

In this study, SADDCP is employed to enhance PPP performance in high-multipath environments through a loosely coupled integration using forward and reverse Kalman filtering. The 3D precise relative positioning provided by SADDCP, when three or more healthy satellites are available, is used to bridge gaps in the PPP absolute solution when it is either completely lost (fewer than five satellites) or degraded due to ambiguity convergence requirements. When only two healthy satellites are detected, the same integration strategy is applied, yielding a planar enhanced solution until full PPP availability is restored. Future work will extend this research to investigate the integration of the enhanced solution with Micro-Electro-Mechanical Systems (MEMS)-based Inertial Navigation Systems (INS) and vision-based navigation techniques for drone-based surveying applications. This integration is expected to improve the quality of

exterior orientation parameters for aerial imagery and reduce processing time in automated image-matching workflows. Additional related research conducted at Benghazi University in the areas of drone-based surveying and vision-based navigation enhancement can be found in [21–25].

2. Objectives & Methodology

In this paper, SADDCP is employed to enhance the performance of Kinematic PPP in high-multipath environments through a loosely coupled integration of the two positioning techniques using forward and reverse Kalman filtering. Within this framework, the three-dimensional (3D) precise relative positioning provided by SADDCP, when three or more healthy satellites are available, is used to bridge gaps in the PPP absolute solution when it is completely lost due to the detection of fewer than five healthy satellites, or when it is degraded because additional time is required to resolve integer ambiguities and achieve convergence after the fifth satellite is detected. When only two healthy satellites are available, the same integration strategy is applied; however, the enhanced solution is determined in a two-dimensional (2D) plane rather than in 3D until full PPP availability is restored. Experimental tests were conducted in diverse GNSS environments along a known pre-surveyed route, transitioning from open-sky conditions to dense urban areas characterized by tall buildings and dense tree coverage. The route was designed to include segments aligned with both the north–south and east–west directions, enabling precise evaluation of the easting and northing components of the raw kinematic PPP and enhanced solutions. In terms of height, the route was selected to be nearly flat, with elevation variations limited to ± 1 cm, facilitating straightforward assessment of solution performance in the vertical component.

3. The integration mathematical description

3.1. SADDCP relative positioning

The GPS carrier phase observable in meters can be written as [6]:

$$CP_{(s,r)(k)} = p_{(s,r)(k)} + c(dT_{(s)(k)} - dt_{(r)(k)}) + dion_{(s,r)(k)} + dtrop_{(s,r)(k)} + dor_{(s)(k)} + E_{(s,r)(k)} + L \cdot N$$

where,

$CP_{(s,r)(k)}$	the carrier phase observation (m)
$p_{(s,r)(k)}$	the true range between receiver (r) and satellite (s) at epoch (k)
c	the speed of light
$dT_{(s)(k)}$	the clock error of satellite (s) at epoch (k)
$dt_{(r)(k)}$	the clock error of receiver (r) at epoch (k)
$dion_{(s,r)(k)}$	the ionospheric delay error between receiver (r) and satellite (s) at epoch (k) (m)
$dtrop_{(s,r)(k)}$	the tropospheric delay error between receiver (r) and satellite (s) at epoch (k) (m)
$dor_{(s)(k)}$	the orbit error of satellite (s) at epoch (k) (m)
$E_{(s,r)(k)}$	the measurement noise including multipath between receiver (r) and satellite (s) at epoch (k)
L	the carrier wavelength (m)
N	the unknown integer ambiguity (cycle)

The true range between receiver (r) and satellite (s) at epoch (k) can be written as:

$$p_{(s,r)(k)} = [(X_{(s)} - X_{(r)})^2 + (Y_{(s)} - Y_{(r)})^2 + (Z_{(s)} - Z_{(r)})^2]^{0.5}$$

where, X , Y and Z are the satellite and receiver Cartesian coordinates.

In SADDCP, the first single differencing is formed between one receiver (r), one satellite (s) and two adjacent epochs (k) & ($k + 1$). The single differencing equation can be written as:

$$SD_{(s)(r)(k+1,k)} = CP_{(s,r)(k+1)} - CP_{(s,r)(k)}$$

$$CP_{(s,r)(k+1)} = [p_{(s,r)(k+1)} + c(dT_{(s)(k+1)} - dt_{(r)(k+1)}) + dion_{(s,r)(k+1)} + dtrop_{(s,r)(k+1)} + dor_{(s)(k+1)} + E_{(s,r)(k+1)} + L \cdot N]$$

$$CP_{(s,r)(k)} = [p_{(s,r)(k)} + c(dT_{(s)(k)} - dt_{(r)(k)}) + dion_{(s,r)(k)} + dtrop_{(s,r)(k)} + dor_{(s)(k)} + E_{(s,r)(k)} + L \cdot N]$$

where,

$SD_{(s)(r)(k+1,k)}$ single differencing between receiver (r), one satellite (s) and two epochs (k) & ($k + 1$)

From the single differences, the double difference ambiguity is removed as long as the integer ambiguity remains constant and the receiver keeps lock the satellite signal. Satellite clock error is reduced based on the stability of the satellite clock over transmission times. Satellite orbit errors are reduced significantly based on the high correlation between the satellite orbit errors over time. Ionosphere and troposphere errors are reduced to the change in delay across the interval. Multipath remains and can be reduced based on the multipath correlation over time. However, receiver clock error is doubled and receiver measurements noise increases. The final formula of single differences equation can be written as:

$$SD_{(s)(r)(k+1,k)} = p_{(s)(r)(k+1,k)} - c dt_{(r)(k+1,k)} + E_{(s)(r)(k+1,k)}$$

The second differencing in SADDCP is carried out between two single differences, similar to that in equation (3), cross two satellites (s) and (j). This can be written as:

$$DD_{(s,j)(r)(k+1,k)} = SD_{(s)(r)(k+1,k)} - SD_{(j)(r)(k+1,k)}$$

$$SD_{(s)(r)(k+1,k)} = [p_{(s)(r)(k+1,k)} - c dt_{(r)(k+1,k)} + E_{(s)(r)(k+1,k)}]$$

$$SD_{(j)(r)(k+1,k)} = [p_{(j)(r)(k+1,k)} - c dt_{(r)(k+1,k)} + E_{(j)(r)(k+1,k)}]$$

where,

$DD_{(s,j)(r)(k+1,k)}$ double differences between one receiver (r), epochs ($k+1$) & (k), and satellites (s) & (j).

Receiver clock error is cancelled out in the double differences. This is extremely important for getting accurate results where the oscillators in low-cost receivers vary in frequency with temperature and pressure making the receiver clock unreliable [6]. The final formula of double differences equation can be written as:

$$DD_{(s,j)(r)(k+1,k)} = p_{(s,j)(r)(k+1,k)} + E_{(s,j)(r)(k+1,k)}$$

The only unknowns in this equation are the receiver Cartesian coordinates in the two epochs (k) & ($k+1$). The changes in the receiver positions between the two epochs can be determined by fixing the coordinated of the receiver at epoch (k) (as zeros for example) and solving for the receiver coordinated at epoch ($k+1$). To determine the relative position of the receiver at epoch ($k + 1$) from (k), the double differences equation should be written as:

$$b = A X + v$$

where,

b the measurement vector with a size of (number of epochs -1, 1)

X the parameter vector with a size of (number of epochs * 3, 1) which include the change in Cartesian position across the interval

A matrix with a size of (number of epoch -1, number of epoch * 3) which relates the parameters to the states

v a vector of random noise with a size of (number of epochs -1, 1)

This equation can then be solved by least squares as:

$$X = (A^T w A)^{-1} A^T w b$$

where,

w the weight matrix with a size of (number of epochs -1, number of epochs -1) which is based on the average satellite residuals obtained from the stand-alone code positioning calculations.

As the SADDCP relative solution depend mainly on carrier phase measurements, cycle slips can happen when losing the connection between satellite and receiver. In this case, a random integer number of cycles is added to the carrier measurements in the GPS data file. Cycle slips can be detected by comparing the differences between the code and carrier phase measurements of two adjacent epochs which is the method used in SADDCP MATLAB code. Code positioning provides continuous solution as long as four satellites can be detected and it is not necessary for the same satellites to be detected adjacent epoch where the code position in each moment is independent solution. When adequate number of satellites is available, the carrier measurement including cycle slip is removed for more precise

solution [1]. As the receiver clock error is removed with SADDCP, the minimum number of satellite required to get the relative positioning is 3 [4]. If the number of free-cycle slips phase measurements is less than 3, pseudo-range measurements are used to fix the gap in phase measurements to be used in the relative solution. Satellite residuals should be statically investigated to remove the outliers. Data Snooping Method is used with SADDCP. Firstly, the covariance matrix of satellite residuals should be determined. Then, the square roots of the diagonal elements are extracted giving the standard deviation of each observation. The residual of each observation is divided with its standard deviation. This value should fluctuate from 0 to 3 depending on the required confidence level. With 99% confidence level chosen in this paper, the critical value is nearly 2.6 so any value bigger than this is detected as an outlier with 1% probability of rejection the observation when it should be accepted (type 1 error) [8].

3.2. The integration of SADDCP / kinematic PPP solution

Kalman filter (KF) filters measurements based on the expected changes of these measurements over time and the statistical properties of the system measurement errors. The filter determines the minimum error estimate of the states based on the linear relation between the measurements and these states. The states are composed of number of values that adequate to define the system motion [7]. KF consists of measurement model and dynamic model which will be illustrated here to define the basic elements as related to the integration of SADDCP with kinematic PPP positioning. As for the equations of propagation and update steps, they are well documented in different sources and there is no point for repeating here.

The measurement model defines the mathematical linear relationship between the measurements and the filter states. The discrete measurement model at the epoch (k) can be defined as:

$$Z_{(k)} = H U_{(k)} + v_{(k)}$$

where,

$Z_{(k)}$ the vector of measurements at the epoch (k)

$U_{(k)}$ the system state vector at the epoch (k)

H the design matrix measurement which defines the linear relationship between the states and the measurements

$v_{(k)}$ the measurement residual vector

The dynamic model describes the change in the state vector parameters over time. The discrete dynamic Model between epochs ($k+1$) & (k) can be given as:

$$U_{(k+1)} = M U_{(k)} + W_{(k)}$$

where,

M the state transition matrix that defines the relation between state vector parameters over time.

$W_{(k)}$ the system noise is approximated based on the sampling interval, the spectral density matrix and standard deviations of the driving noise of the system.

In the case of integrating kinematic PPP positioning with SADDCP, the vector of measurements includes six observations; three observations from the absolute kinematic PPP positioning of epoch k ($X_{(k)}$, $Y_{(k)}$, $Z_{(k)}$) and three values describing the 3D changes in positioning between epochs k & $k+1$ ($dX_{(k, k+1)}$, $dY_{(k, k+1)}$, $dZ_{(k, k+1)}$). As there are no unknowns, the $Z_{(k)}$ and $U_{(k)}$ are the same vector, H is a (6*6) unit matrix and $v_{(k)}$ equal zero.

$$Z_{(k)} = U_{(k)} = [X_{(k)} \ Y_{(k)} \ Z_{(k)} \ dX_{(k, k+1)} \ dY_{(k, k+1)} \ dZ_{(k, k+1)}]^T$$

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

As for the dynamic model, the system state vector at the epoch ($k+1$) includes three observations from the absolute kinematic positioning for this epoch ($X_{(k+1)}$, $Y_{(k+1)}$, $Z_{(k+1)}$) and three values describing the 3D changes in positioning between this epoch and the previous one ($dX_{(k, k+1)}$, $dY_{(k, k+1)}$, $dZ_{(k, k+1)}$). The system state vector can be defined as:

$$U_{(k+1)} = [X_{(k+1)} \ Y_{(k+1)} \ Z_{(k+1)} \ dX_{(k, k+1)} \ dY_{(k, k+1)} \ dZ_{(k, k+1)}]^T$$

The enhanced kinematic PPP positioning in epoch $k+1$ can be defined as:

$$X_{(k+1)} = X_{(k)} + dX_{(k, k+1)}$$

$$Y_{(k+1)} = Y_{(k)} + dY_{(k, k+1)}$$

$$Z_{(k+1)} = Z_{(k)} + dZ_{(k, k+1)}$$

To relate the state vectors in epoch $k+1$ with that in epoch k , the state transition matrix (M) should be written as:

$$M = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The standard deviations for the carrier phase measurements used in the system noise vector $W(k)$ in the dynamic model is computed using the signal to noise ratio obtained directly from the receiver RXMRAW message. The standard deviation of carrier phase measurements tends to round about millimeters in multipath-free environment and reaches the quarter of the GPS wavelength (5cm) as a maximum value [4]. As for the quality of kinematic PPP solution, GrafNav software has been used to process the raw GNSS collected data with final products, and the results already includes the standard deviation values of each component at each epoch. In this paper, the differences between the computed enhanced position at epoch $(k+1)$ and the kinematic PPP at the same epoch will be used as an indication on the quality of the PPP solution at the next epoch. The integration of SADDCP and kinematic PPP positioning is presented in the following workflow diagram which has been implemented by the author in MATLAB.

3.3. The integration solution workflow

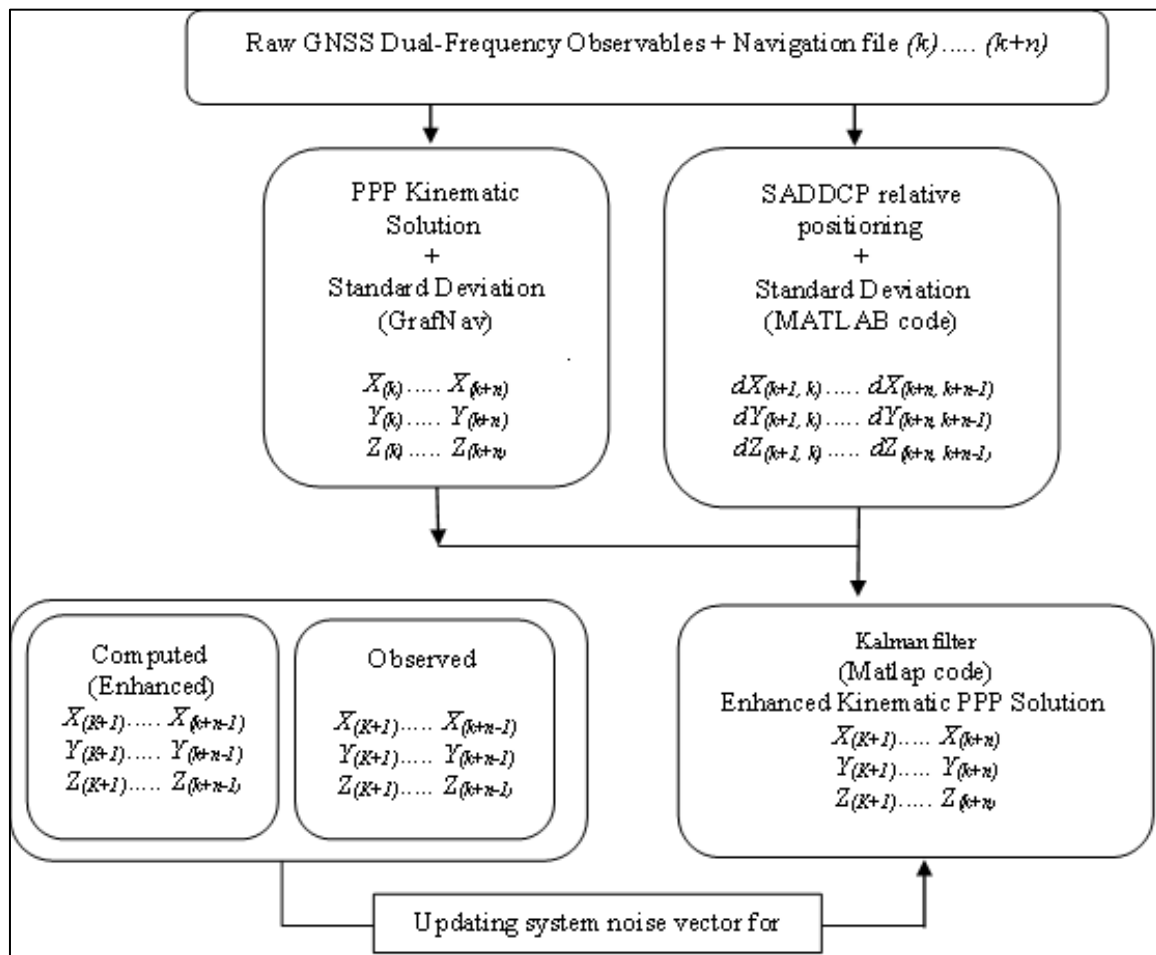


Figure 1 Workflow diagram of SADDCP / kinematic PPP integration

4. Tests, results and discussion

To evaluate the suggested integration between SADDCP and Kinematic PPP solution, experimental tests were conducted in diverse GNSS environments along a known pre-surveyed route, transitioning from open-sky conditions to dense urban areas characterized by tall buildings and dense tree coverage. The route was designed to include segments aligned with both the north-south and east-west directions, enabling precise evaluation of the easting and northing components of the raw kinematic PPP and enhanced solutions. In terms of height, the route was selected to be nearly flat, with elevation variations limited to ± 1 cm, facilitating straightforward assessment of solution performance in the vertical component. Dual-frequency Leica GNSS receiver has been fixed on a manual trolley for the route to be precisely tracked and 1 Hz kinematic data has been collected for nearly one hour. Figure 2 shows the testing area, pre-surveyed route, and zones with weak GNSS signals. Figure (3) illustrates the raw PPP kinematic solution and the enhanced integrated solution in all testing area. Figures (4), (5), & (6) show both solutions in open-sky areas, weak signal & mid-multipath environments, and GNSS off & high multipath areas, respectively. Table (1) illustrates the quality as Root Mean Square Error (RMSE) of the two solutions in E, N & H in open-sky areas and in mid-multipath weak signal environments. The table also includes the percentage of continuity for both solutions.



Figure 2 Testing pre-surveyed route with weak GNSS signal zones



Figure 3 Raw kinematic PPP Vs. SADDCP/PPP integration in all testing area



Figure 4 Raw kinematic PPP Vs. SADDCP/PPP integration in open-sky areas



Figure 5 Raw kinematic PPP Vs. SADDCP/PPP integration in partially obscured sky



Figure 6 Raw kinematic PPP Vs. SADDCP/PPP integration in heavily obscured sky areas

Table 1 The quality of raw kinematic PPP & SADDCP/PPP solution in different GNSS coverage levels

Solution Type	Open-Sky Areas				
	Quality of E Component RMSE (m)	Quality of N Component RMSE (m)	Quality of H Component RMSE (m)	3D Solution Continuity %	2D Solution Continuity %
Raw PPP Kinematic Solution	0.0288	0.0363	0.0451	100%	#
SADDCP/PPP Integrated Solution	0.0262	0.0327	0.0375	100%	No need
Solution Type	Partially Obscured Sky Areas				
	Quality of E Component RMSE (m)	Quality of N Component RMSE (m)	Quality of H Component RMSE (m)	3D Solution Continuity %	2D Solution Continuity %
Raw PPP Kinematic Solution	1.03	1.44	1.89	100%	#
SADDCP/PPP Integrated Solution	0.37	0.56	0.74	100%	100%
Solution Type	Heavily Obscured Sky Areas				
	Quality of E Component RMSE (m)	Quality of N Component RMSE (m)	Quality of H Component RMSE (m)	3D Solution Continuity %	2D Solution Continuity %
Raw PPP Kinematic Solution	2.64	3.26	5.37	21%	#
SADDCP/PPP Integrated Solution	0.71	1.03	1.69	65%	89%

Starting with open-sky areas, Table (1) and Figure (4) show that the quality of the raw kinematic PPP solution is within 3 to 5 cm in all components, with 3D continuity of 100%, which is reasonable and expected. The quality of the kinematic PPP solution can reach the level of 1 to 2 cm in areas completely free from multipath effects where the sky is open from horizon to horizon. However, this is not the case in the testing area, as the route is surrounded by buildings and trees. The quality of the integrated solution in open-sky areas is close to that of the raw PPP solution, with slight enhancement, especially in the H component. This improvement can be attributed to the fact that the SADDCP solution requires at least 3 satellites, which increases the likelihood of selecting the best available satellite-receiver observables with the smallest standard deviation values. This is not the case with the raw kinematic PPP solution, where at least 5 satellites with known ambiguity numbers are required to obtain a solution. This requirement may reduce the opportunity for PPP to select the best observables, especially when the number of available satellites is limited. Another possible reason is the capability of the SADDCP solution to mitigate low-level multipath effects in open-sky areas by exploiting the correlation of this error over adjacent epochs. The integrated solution is mainly influenced by the quality of the two individual solutions in each component. It detects the highest-quality points from the raw kinematic PPP solution and uses them as reference absolute points for the forward and reverse Kalman Filter (KF) integration. Based on these reference points, the integration process determines the solution of subsequent epochs according to the standard deviation values of both techniques, where the resulting solution leans toward the individual solution with the highest precision.

The use of forward and reverse KF integration is motivated by the fact that errors in the SADDCP solution accumulate over time and increase with distance from the reference points. Therefore, employing both forward and reverse solutions significantly improves the final solution and overcomes the cumulative error limitation of SADDCP. The 100% continuity of the raw PPP solution is attributed to maintaining connections with at least 5 satellites during the observation period. Consequently, SADDCP also provides 100% continuity, since it requires only 3 satellites for a 3D solution and 2 satellites for a 2D solution.

In partially obscured sky, where the trajectory passes under low-density trees and near medium to high-rise buildings, the number of visible satellites tends to decrease and satellite geometry becomes weaker. Such environments are suitable for multipath and reflected signals. Multipath errors may reach several meters when using code measurements and several centimeters for carrier phase measurements, provided that the satellite-receiver connection persists. The GNSS system used in this test is equipped with a right-hand circular polarization (RHCP) pinwheel antenna to mitigate reflected signals. Since satellite signals are transmitted using RHCP, their polarization may change depending on the reflection angle and the number of reflections. Using an RHCP antenna helps reject most reflected signals. However, left-hand circular polarization (LHCP) signals resulting from multiple reflections may still be received by the antenna, and the receiver may not fully mitigate their effect. Some receivers, including the one used in this test, apply a narrow correlator technique to distinguish direct signals from reflected ones based on arrival time and signal strength. However, if only reflected signals are received because the satellite is blocked by obstacles, detecting multipath becomes very difficult even with this technique.

Table (1) and Figure (5) show that the quality of the raw PPP solution improves when integrated with SADDCP by approximately 0.7 m, 0.9 m, and 1.15 m in the E, N, and H components, respectively. Since multipath effects in carrier phase measurements typically do not exceed 5 cm in open-sky areas and are at the decimeter level in multipath environments, the significant degradation of the raw PPP and integrated solutions in these areas compared to open-sky areas can mainly be attributed to loss of satellite lock and the formation of cycle slips. Cycle slips reduce the number of available healthy observations, decrease the degrees of freedom of the solution, and limit the effectiveness of statistical techniques for detecting and rejecting outliers. Surrounding buildings not only mask satellites intermittently, causing cycle slips, but multipath can also disturb code correlation between satellite and receiver, leading to loss of lock. If both direct and reflected signals are received simultaneously, code correlation may be degraded, potentially resulting in loss of lock. If only reflected signals are received, two scenarios are expected; in the first, just one reflected signal is received and the connection with the satellites is not affected and the second scenario is when more than one reflected signal from the same satellite are received by the antenna. In this case, the connection with the satellite might be affected depending on the strength of the received signals. Increased multipath levels may also generate electromagnetic noise around the antenna, affecting its directivity and radiation pattern. Consequently, signals arriving from low-gain directions may not be properly received, degrading positioning quality. Some post-processing software, such as GrafNav, mitigates multipath by analyzing satellite residuals and removing satellites with large residuals before recalculating the position. However, this approach is only effective when a sufficient number of satellites is available. With a limited number of satellites, rejecting poor observations may result in losing the entire solution.

The degradation in partially obscured areas is also related to weak satellite geometry. Often, only high-elevation satellites are visible, and they may occupy a narrow sector of the sky, resulting in poor geometric strength. This particularly increases altitude errors due to small satellite intersection angles. Results indicate that planimetric accuracy is generally better than altitude accuracy, which can also be attributed to satellite geometry. Theoretically, optimal geometry is achieved with 5 satellites: four distributed approximately 90° apart in azimuth at 40–50° elevation, and one near the zenith. Increasing the number of overhead satellites improves plan accuracy but may reduce vertical accuracy, and vice versa. Low-elevation satellites are often excluded due to increased atmospheric delay and noise. GNSS positioning assumes signal propagation in vacuum, but low-elevation signals travel through more atmosphere, leading to larger delays and reduced precision. The results also show that accuracy in the E–W direction is generally better than in the N–S direction, which is consistent with satellite orbital geometry. GPS satellites have an inclination of 55°, meaning they operate between +55° and –55° latitude. Consequently, at higher latitudes, satellites are predominantly observed overhead and toward the E, W, and S directions, with fewer satellites in the northern direction and often at low elevation angles.

In heavily obscured sky environments, the advantages of the integrated solution become more evident. The raw PPP solution degrades significantly, reaching errors of several meters in both plan and height. Raw PPP provides coverage for only 21% of the heavily obscured trajectory. In contrast, the integrated solution achieves continuity percentages of 65% and 89% for 2D and 3D solutions, respectively, with accuracies of approximately 1.3 m in plan and 1.7 m in height. In open-sky conditions, up to 20 satellites may be available with good dilution of precision (DOP), enabling both techniques to select the best observations with minimal residuals. During this time, ambiguities of newly observed

satellites can converge before being utilized in the PPP solution. However, in heavily obscured areas, satellite visibility decreases, geometry weakens, and multipath effects intensify, degrading solution quality. If the number of connected satellites remains ≥ 5 , raw PPP is mainly affected by geometry and multipath. When the number of satellites with fixed ambiguities drops below 5, raw PPP degrades significantly due to cycle slips and the need to use observations with imprecise ambiguity estimates derived from code measurements.

In such cases, SADDCP continues to operate without being affected by cycle slips, providing a 3D solution with ≥ 3 satellites and a 2D solution with ≥ 2 satellites. Figure (6) shows segments where both solutions fail due to satellite visibility dropping below 2 in dense tree areas. The figure also indicates that the integrated solution degrades when operating for extended periods without PPP updates, due to the cumulative nature of SADDCP errors. Furthermore, the integrated solution strongly depends on the quality of PPP reference points; if these reference points are biased, the entire integrated trajectory will be biased, resulting in a parallel offset from the true path.

5. Conclusion

In this paper, SADDCP was employed to enhance the performance of the raw kinematic PPP solution through loosely coupled integration using forward and reverse Kalman filtering. In this integrated scheme, the precise 3D relative positioning provided by SADDCP, when three or more healthy satellites are available, is used to bridge gaps in the PPP absolute solution when it is completely unavailable due to fewer than five detected healthy satellites, or when it is degraded during ambiguity resolution and convergence after the fifth satellite is re-acquired. When only two healthy satellites are available, the same integration strategy is applied, but the enhanced solution is limited to a planar (2D) solution until the PPP solution is restored. Experimental tests were conducted in various GNSS environments along a known pre-surveyed route, transitioning from open-sky conditions to dense urban areas characterized by tall buildings and dense tree coverage. The integration approach was evaluated under different GPS environments to ensure comprehensive assessment. The results demonstrate the ability of the integrated solution to combine the strengths of both techniques, thereby providing an improved absolute kinematic positioning solution. The integration particularly benefits from the lower satellite requirement of SADDCP, which helps mitigate the degradation of PPP performance in partially and heavily obscured environments. In open-sky areas, the raw kinematic PPP solution achieves an accuracy of 3 to 5 cm in all components with 3D continuity of 100%. The integrated solution exhibits comparable performance with slight improvement, especially in the H component. In partially obscured sky environments, the integration improves the raw PPP solution by approximately 0.7 m, 0.9 m, and 1.15 m in the E, N, and H components, respectively, while maintaining 100% continuity for both solutions. In heavily obscured environments, raw PPP covers only 21% of the trajectory, with errors reaching several meters. In contrast, the integrated solution achieves continuity percentages of 65% (2D) and 89% (3D), with accuracies of approximately 1.3 m in plan and 1.7 m in height. Overall, this investigation demonstrates the considerable capability of the SADDCP to enhance the performance of raw kinematic PPP, particularly in partially and heavily obscured sky conditions. Future work will focus on integrating SADDCP, kinematic PPP, and MEMS-based INS to investigate the potential for reducing the limitations of the current SADDCP/PPP integration, particularly regarding solution outages in heavily obscured environments and solution drift when moving away from raw PPP reference points.

References

- [1] Hofmann-Wellenhof B, Lichtenegger H, Wasle E. GNSS global navigation satellite systems: GPS, GLONASS, Galileo, and More. 2007
- [2] Amami M, Smith M, Kokkas N. Low-Cost Vision Based Personal Mobile Mapping System. ISPRS- International Archives of The Photogrammetry, Remote Sensing and Spatial Information Sciences. 2014; XL-3/W1: 1-6.
- [3] Amami M. A Novel Design Concept of Cost-Effective Permanent Rail-Track Monitoring System. World Journal of Advanced Research and Reviews. March 2022; 13(3): 451-473.
- [4] Amami M. Investigations into the quality of final-product dual frequency kinematic PPP in open sky using CSRS-PPP free online service: GPS Vs. GPS+GLONASS. Global Journal of Engineering and Technology Advances (GJETA). November 2025; 25(2):138-143.
- [5] Amami M. The Advantages and Limitations of Low-Cost Single Frequency GPS/MEMS-Based INS Integration. Global Journal of Engineering and Technology Advances. Feb. 2022; 10(2): 018-031.
- [6] Amami M. The Integration of Stand-Alone GPS Code Positioning, Carrier Phase Delta Positioning and MEMS-Based INS. International Research Journal of Modernization in Engineering Technology and Science. March 2022; 4(3): 700-715.

- [7] Amami M. The Integration of Image-Based Navigation and GPS Carrier Phase Delta Positioning for Aerial Triangulation using Low-Cost Drones with Limited Number of Ground Control Points. *Quest Journals*. 2022; 7(5): 23-31.
- [8] Amami M. The Integration of Time-Based Single Frequency Double Differencing Carrier Phase GPS/ Micro-Electromechanical System-Based INS. *International Journal of Recent Advances in Science and Technology*. Dec. 2018; 5(4): 43-56.
- [9] Amami M. Investigations into the quality of final-product dual-frequency static PPP over fixing time using CSRS-PPP free online service: GPS Vs. GPS + GLONASS. *World Journal of Advanced Engineering Technology and Sciences (GJETA)*. November 2025; 17(2): 438-443.
- [10] Amami M. Enhancing Stand-Alone GPS Code Positioning Using Stand-Alone Double Differencing Carrier Phase Relative Positioning. *Journal of Duhok University (Pure and Eng. Sciences)*. 2017; 20(1): 347-355.
- [11] Amami M. Kinematic PPP Using PPP-WIZARD Free Online Service: GPS Vs. GPS + GLONASS. *International Research Journal of Modernization in Engineering Technology and Science*. December 2025; 7(12): 3445-3451.
- [12] Amami M, Fadeil A. Investigations into the quality of Kinematic PPP in open-sky using final-product APPS free online GPS-alone service. *GSC Advanced Research and Reviews*. January 2026; 26(1): 023-028
- [13] Amami M. Quality of Static PPP over observation time using PPP-WIZARD free online service: GPS Vs. GPS + GLONASS. *Open Access Research Journal of Science and Technology*. December 2025; 15(2): 195-200
- [14] Amami M, Fadeil A. Evaluating The Quality Of Static PPP Over Observation Time Using APPS Free Online GPS-Alone Service. *International Journal of Engineering Development and Research*. January 2026; 14(1): 787-792
- [15] Amami M. Testing Patch, Helix and Vertical Dipole GPS Antennas with/without Choke Ring Frame. *International Journal for Research in Applied Sciences and Engineering Technology*. Feb. 2022; 10(2): 933-938.
- [16] Amami M. Fast and Reliable Vision-Based Navigation for Real Time Kinematic Applications. *International Journal for Research in Applied Sciences and Engineering Technology*. Feb. 2022; 10(2): 922-932.
- [17] Amami M, EL-Turki A, Rustum A, EL-Amaari I, Jabir T. Topographic Surveying using low-cost amateur drones and 4K ultra-high-definition videos. *Open Access Research Journal of Science and Technology*. April 2022; 4(2): 072-082.
- [18] Amami M, Elmehdwi A, Borgaa A, Buker A, Alareibi A. Investigations into utilizing low-cost amateur drones for creating ortho-mosaic and digital elevation model. *International research journal of modernization in engineering technology and science*. March 2022; 4(3): 2107-2118.
- [19] Amami M. Dual-Frequency Static PPP Over Fixing Time Using Final-Product Free Online Services: CSRS-PPP Vs. PPP-WIZARD Vs. APPS. *Global Journal of Engineering and Technology Advances*. February 2026; 26(02): 039-047
- [20] Amami M. Dual-Frequency Kinematic PPP in Free-Multipath Open-Sky: CSRS-PPP vs. PPP-WIZARD Vs. APPS. *International Journal for Research in Applied Science & Engineering Technology*. February 2026; 14(I): 1005-1014.
- [21] Amami M. Comparison Between Multi and Single Epipolar Geometry-Based Filters for Optical Robot Navigation. *International Research Journal of Modernization in Engineering Technology and Science*. March 2022; 4 (3): 476-485.
- [22] Amami M. Comparison Between Multi Epipolar Geometry and Conformal 2D Transformation-Based Filters for Optical Robot Navigation. *International Journal for Research in Applied Sciences and Engineering Technology*. March 2022; 10(3): 388-398.
- [23] Amami M. Comparison Between Multi Epipolar Geometry and Affine 2D Transformation-Based Filters for Optical Robot Navigation. *International Journal for Research in Applied Sciences and Engineering Technology*. March 2022; 10(3): 399-409.
- [24] Amami M. Speeding up SIFT, PCA-SIFT and SURF Using Image Pyramid. *Journal of Duhok University, [S.I.]*. July 2017; 20(1): 356-362.
- [25] Amami M. Multi and Single Epipolar Geometry-Based Filters Vs. Affine and conformal 2D Transformation-Based Filters. *Global Journal of Engineering and Technology Advances*. March 2022; 10(3): 032-051.