Performance of a Low-Cost GNSS Receiver Using MADOCA Corrections with Precise Point Positioning (PPP) Mode in Thailand

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Abstract

To achieve centimeter-level GNSS positioning, an augmentation system is necessary to correct for several sources of GNSS errors, including ionospheric and tropospheric delays, satellite orbit and satellite clock errors, as well as multipath interference. The high-precision positioning systems, such as real-time kinematic (RTK) and precise point positioning (PPP), typically rely on precise satellite orbit and clock data derived from a global network of GNSS reference stations. Since the launch of the QZSS L6E signal, known as the Multi-GNSS Advanced Demonstration Tool for Orbit and Clock Analysis (MADOCA), this precise system for estimating orbit and clock has been extensively utilized in various fields, particularly in the automated vehicle operation, controlled construction, and agricultural machinery. In Thailand, the QZSS can typically be visible at elevation angles ranging from 15 to 60 degrees. As a result, the receiver can obtain real-time MADOCA messages directly from the satellite. Typically, high-precision positioning is always achieved using survey-grade equipment, which is expensive. However, it would be advantageous to develop accurate outcomes through low-cost equipment. The study focuses on evaluating the performance of MADOCA augmentation by using a low-cost GNSS receiver in both static and kinematic PPP approaches, executed in different scenarios. In a static test performed in an open-sky scenario, the results indicate that the root mean square error (RMSE) is 0.060 meters horizontally and 0.072 meters vertically. The RMSE in a multipath environment is 0.877 meters, whereas the vertical RMSE is 1.335 meters. Finally, the kinematic test provided horizontal and vertical RMSEs of 3.130 meters and 13.544 meters, respectively.

Keywords: Low-cost GNSS receiver, MADOCA, Precise point positioning (PPP), QZSS

1. Introduction

The Japanese Quasi-Zenith Satellite System (QZSS) currently comprises three satellites in quasi-zenith orbit (QZO) and one satellite in geostationary orbit (GEO). By 2026, QZSS will become seven satellite constellations to provide cover area services in the Asia-Oceania region [1]. The QZSS navigation signals also broadcast the L6 signal (1275.46 MHz), which delivers correction messages to correct several sources of GNSS errors. However, there are limitations in the accuracy of positioning at the meter level [2].

The Japan Aerospace Exploration Agency (JAXA) developed a precise GNSS orbit and clock estimate system named Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis (MADOCA). These binary format messages are transmitted via L6E signals, which are streamed in real time from several CORS stations worldwide. MADOCA can support multiple GNSS systems, including GPS, GLONASS, and QZSS. However, support for Galileo and BeiDou is currently being developed. Typically, MADOCA products, such as orbit, clock, and high-rate clock correction, including user range accuracy (URA), can be acquired in three ways. The first is directly from L6E in the QZSS service area. The second option is to receive via the internet, and the last one is to use offline mode [3].

Several previous studies have attempted to evaluate the efficiency of MADOCA in achieving accurate positioning. Some studies have utilized MADOCA augmentation messages through static PPP using both survey-grade and low-cost receiver [4][5][6][7] and [8].

The results demonstrated centimeter-level positional improvement in almost all directions, despite performing in a multipath interference environment [6] and [7]. In addition, kinematic PPP is extensively incorporated with MADOCA as well [5][6][7] and [9]. The study revealed that MADOCA has the potential to enhance location accuracy at the meter level, because of factors such as receiver type, test environment, and cycle slips, including vehicle speed. Nevertheless, the MADOCA system exhibits potential for improving accuracy in positioning. It is also compatible with many positioning methods, such as post-processing and real-time processing, making it advantageous for any application associated with location-based services.

For Thailand, the MADOCA system has not yet been opened for public service. Because of Thailand's geographic location in Southeast Asia, the QZSS satellite can be tracked within an angular range of 15-60 degrees [7] and [10] as shown in Figure 1. This enables the direct reception of real-time correction signals from the QZSS satellite.

HDOP : 12.90
VDOP : 4.66
Visible GNSS : 4
QZS : 4 GPS : 0 GLO : 0
BDS : 0 GAL : 0 SBS : 0

Figure 1: An illustration of visible QZSS satellites in Bangkok, the capital city of Thailand

Over the past few years, the MADOCA system has undergone testing in various industries in Thailand that require real-time with high accurate location. The smart agriculture system is an example of a use case. Utilizing the RTK technique, which interfaces with CORS and the MADOCA, autonomous agricultural machinery tracks its trajectory. As a result, this system provides a high-precision positioning result within 5 cm for a tractor robot sensor, without causing damage to cultivated crops by the tractor wheel [10] and [11]. Furthermore, there are ongoing plans to undertake experiments in other areas, such as an automation in manufacturing, autonomous driving, risk monitoring systems and maritime navigation, where GNSS alone without augmentation system does not give adequate precision.

The objective of this study is to investigate the effectiveness of MADOCA enhancement in a low-cost receiver. At present, there is an increasing demand for affordable equipment that offers high performance. Due to the precise centimeter-level position provided by MADOCA, it may not be necessary to employ expensive survey-grade receivers. In addition, a real-time MADOCA system also receives data from the Thailand CORS station through streaming, which provides an advantage for use in many areas of development. This study conducted experiments using two positioning methods: static and kinematic PPP. The performance of MADOCA will be evaluated by comparing the positioning accuracy, as indicated by the root mean square error (RMSE) and standard deviation. The positioning results achieved from three different scenarios, including an open-sky environment, multipath conditions, and a rural area, are evaluated using both a high-precision survey-grade receiver and a low-cost receiver. According to this investigation, our goal is to achieve centimeter-level accuracy in a position using low-cost equipment, that is minimizing operational costs.

2. Multi-GNSS Advanced Orbit and Clock Augmentation (MADOCA)

MADOCA is a processing tool to estimate precise satellite clock and orbit corrections. These real-time augmentation messages are obtained from the L6E signal, which can be received either directly from the QZSS satellite or through the internet. The estimation of orbit and clock offsets is performed by two methods: post-processing using iterative weighted least squares and real-time processing using extended Kalman filter (EKF) [12]. These techniques make use of observation data streams from the monitoring station network (MGM-net), which was made up from several GNSS tracking stations, host organizations, and data-sharing organizations, as well as the International GNSS Service (IGS) network. Hence, precise orbits and clock offsets are then computed utilizing a huge number of observations from as many as 86 reference stations worldwide.

Table 1: RTCM SSR format [13]

MADOCA Products	Interval		RTCM SSR message		
	Estimation	Provide	GPS	GLONASS	QZSS
Orbit correction	30	1	1057	1063	1246
Clock correction	1	1	1058	1064	1247
HR-clock correction	1	1	1062	1068	1251
URA	1	1	1061	1067	1250

Table 2: MADOCA orbit and clock accuracy [13]

MADOCA Products	Offline			Realtime		
	GPS	GLONASS	QZSS	GPS	GLONASS	QZSS
Orbit correction	3 cm.	7 cm.	7 cm.	6 cm.	9 cm.	9 cm.
Clock correction	0.1 ns	0.25 ns	0.25 ns	0.1 ns	0.25 ns	0.25 ns

At present, the MADOCA real-time products include orbit and clock correction, as well as High rate (HR) clock correction and user range accuracy (URA). These tools currently provide support for GPS, GLONASS, and QZSS. As shown in Table 1. Real-time correction data is transmitted in the RTCM SSR format, with each satellite system having a particular message type. For instance, the code 1057 is used to define the SSR GPS orbit correction, which is provided every second. Typically, MADOCA products can be utilized in three ways. Firstly, in locations where the QZSS is visible, users can immediately receive real-time messages through the QZSS L6E signal, but they must maintain continuous reception of the signal from the satellite. Secondly, a real-time message can be received from an NTRIP server; however, this requires a user account and an internet connection. Third, offline post-processing can retrieve the RTCM3 SSR file from the FTP server. The level of accuracy in orbit and clock correction differs between real-time and offline approaches in each satellite system, as seen in Table 2.

3. Methodology

To evaluate the performance of MADOCA in a low-cost GNSS receiver, experiments were done in different scenarios, each using two positioning modes, static and kinematic PPP. For each test scenario, both a survey-grade receiver and a low-cost receiver were used to compare the positioning results. The process flow was divided into three main parts: data collection, data post-processing, and data validation, organized in the following order.

3.1 Data Collection

Three experiments were set up in the Thailand study area to evaluate MADOCA's positioning accuracy. The static test is divided into two test scenarios, each of which expects to receive a different impact from the error source. In test scenario 1, the antenna for the CORS station named "CUUT" was installed on the rooftop of a 17-floor building at Chulalongkorn University in Bangkok. This scenario is an open-sky area without any signal obstruction (Figure 2). Data was collected for 7-days at a 1-second epoch rate, with static PPP. Two GNSS receivers, survey-grade GNSS reference receiver (Trimble NETR9) and multi-band low-cost receiver (UBLOX ZED F9P-L1/L2/E5B), are used to receive signals through a signal splitter from the single antenna as shown in Figure 3. Test scenario 2 involved executing a 7-day static test, specifically in a multipath condition. The antenna was installed on the rooftop of a 4-floor building located within the university campus. Reflected signals probably affected the antenna due to nearby high-rise buildings (Figure 2). In this test, the CORS station named ‘CUSV’ (owned by the Department of Survey Engineering) served as the reference point for baseline processing. A quad-constellation receiver (CHCi80) and a low-cost multi-band receiver and antenna (UBLOX and Tallysman antenna-TW3972XF) were employed to receive signals in one hour across two periods because of the limitation of an interrupted power supply and the impact of weather conditions.

For the kinematic positioning testing, the Kanchanaburi province's suburban region served as the test scenario 3. There were signal obstacles on the side of the road, such as large trees, residences, and vehicles. Both survey-grade (CHCi80) and low-cost receivers (UBLOX) were mounted on a tricycle sidecar and driven approximately 4.5 kilometers at a consistent velocity to collect data as shown in Figure 4. In this test, the CORS station called 'TKRI' (owned by the Royal Thai Survey Department - RTSD), located near the test route in the same province (approximately baseline 4 kilometers), served as the reference baseline to compare the results from both types of receivers.

Figure 2: Test scenario 1 in the open sky area (left) and scenario 2 in the multipath area (right)

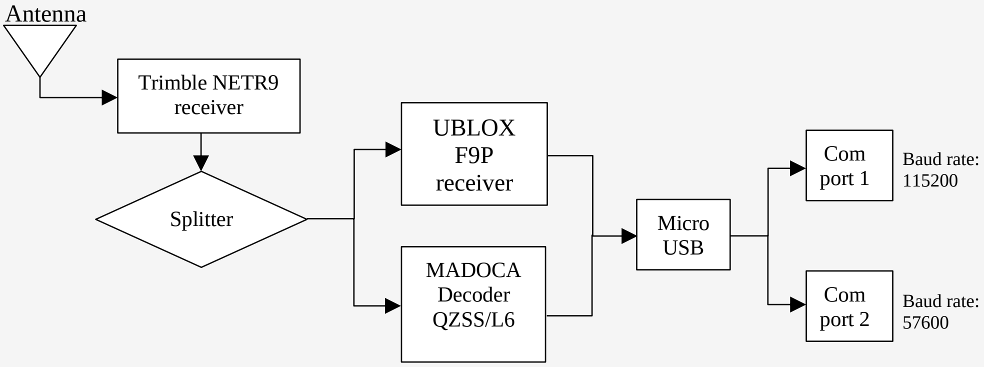

Figure 3: Example of antenna and receiver architecture in test scenario 1

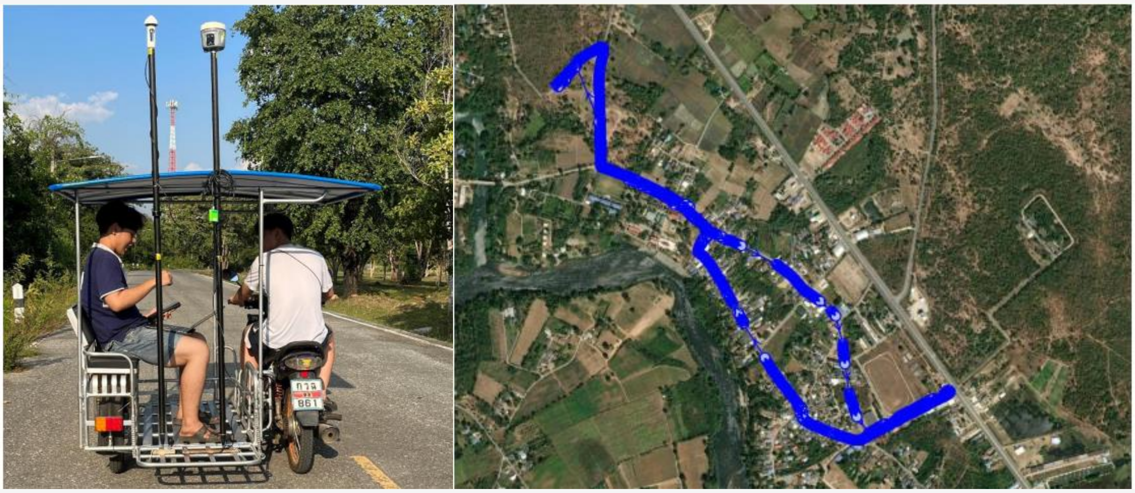

Figure 4: Kinematic positioning in test scenario 3

3.2 Data Post-Processing

The post-processing for the static test based on observation data from survey grade receiver was done using the RTKLIB software program. The orbit and satellite clock corrections were performed with the IGS Final product that included IGS Antenna Phase Center Corrections in ITRF2020. The Finite Element Solution tidal model 2004 (FES2004) was employed for ocean tide loading corrections. Subsequently, the positioning estimation in PPP mode was executed. For low-cost receivers, a real-time orbit and clock correction from MADOCA through the MAD-WIN program (MADOCA PPP processing on the Windows operating system). The output consisted of three separate file formats: a UBX file containing orbit and clock data, an NMEA file containing positioning data, and another UBX file containing observation data. These files served as input for RTKPLOT to analyze statistical errors in positioning. In the kinematic test data collected from both survey-grade and low-cost receivers were processed using a similar approach as described in the static test, with the addition of post-processing kinematic (PPK). The results obtained from both types of receivers were then compared to the reference position achieved by PPK. The experiment used the CORS station, located around 4 kilometers from the receiver, as a reference baseline to determine the fixed location using an online GPS processing service.

3.3 Data Validation

The reference position in each test scenario was determined using observation data obtained from the survey-grade receiver at the base station. The precise coordinates in the international terrestrial reference frame (ITRF) were computed by transmitting the data to the online GPS processing services, namely CSPS-PPP (The Canadian Spatial Reference System), which utilizes the international GNSS service (IGS). As a result, RMSE and standard deviation in both horizontal and vertical directions of a survey-graded receiver and a low-cost receiver were then compared.

4. Results and Discussion

To assess the effectiveness of utilizing the MADOCA products in both low-cost and survey grade receivers, the static and kinematic tests were conducted in three different scenarios: an open-sky environment, a multipath environment, and along-vehicle driving. The root-mean-square error (RMSE) and standard deviation (STD) in both the horizontal and vertical directions were then compared to assess the performance of MADOCA.

4.1 Static Positioning Results

The positioning error, measured by the RMSE and standard deviation, resulting from the static-PPP test performed in an open-sky scenario, is presented in Figure 5 and Figure 6. According to Figure 5, the survey-grade receiver provided an average RMSE of 0.009 meters in the horizontal direction and 0.024 meters in the vertical direction. When utilizing a low-cost receiver with MADOCA corrections, the positioning error increased to 0.060 meters horizontally and 0.072 meters vertically. When determining the standard deviation (Figure 6), the survey grade receiver provided 0.008 meters horizontally and 0.001 meters vertically. The low-cost receiver results were 0.045 meters and 0.070 meters, respectively.

The findings indicated that in this scenario, a survey-grade receiver can achieve positioning accuracy below the millimeter level horizontally and within 5 centimeters vertically. Employing a low-cost receiver (UBLOX F9P) with MADOCA correction and executing real-time processing through the MAD-WIN application resulted in a positioning error that remained below the 10-centimeter level. When evaluating the accuracy achieved, it appears satisfactory in comparison to survey grade satellite receivers. Figure 7 provides the average root mean square error (RMSE) and standard deviation results for the static test conducted in test environment 2, which involved a multipath environment.

The results demonstrated that the survey-grade receiver provided an average RMSE of 0.327meters in the horizontal direction and 0.607 meters in the vertical direction. When utilizing a low-cost receiver with MADOCA corrections, the positioning error increased slightly to 0.877 meters horizontally and 1.335 meters vertically. When determining the standard deviation (Figure 8), the survey grade receiver provided 0.042 meters horizontally and 0.122 meters vertically. The low-cost receiver results were 0.691 and 1.306 meters, respectively. In this case, positioning accuracy from a low-cost receiver using a MADOCA adjustment was lower than that from a survey-grade receiver, but the difference was still under a meter. The difference was approximately 50 centimeters in the horizontal direction, and over 70 centimeters in the vertical direction. Typically, multipath reception has a more significant effect on vertical accuracy than on horizontal accuracy. By utilizing expensive and high-quality equipment, it is possible to significantly mitigate the negative effects of multipath interference. Hence, the results derived from a low-cost receiver can be considered acceptable.

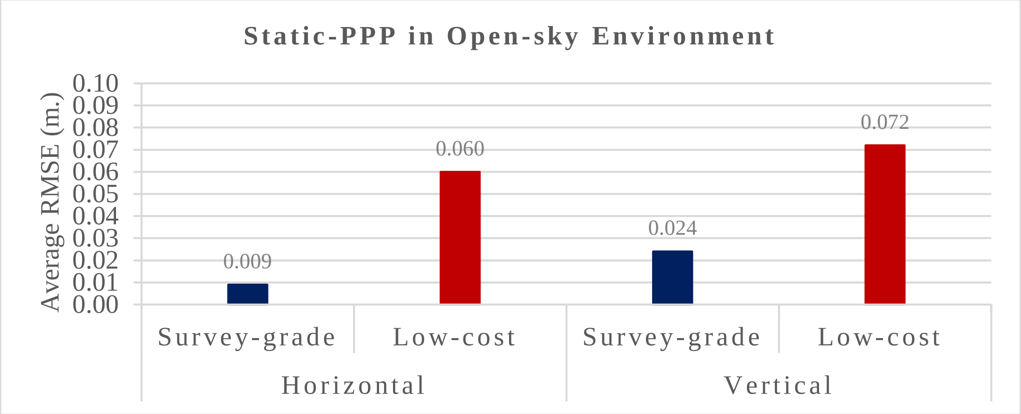

Figure 5: The average RMSE in an open-sky environment

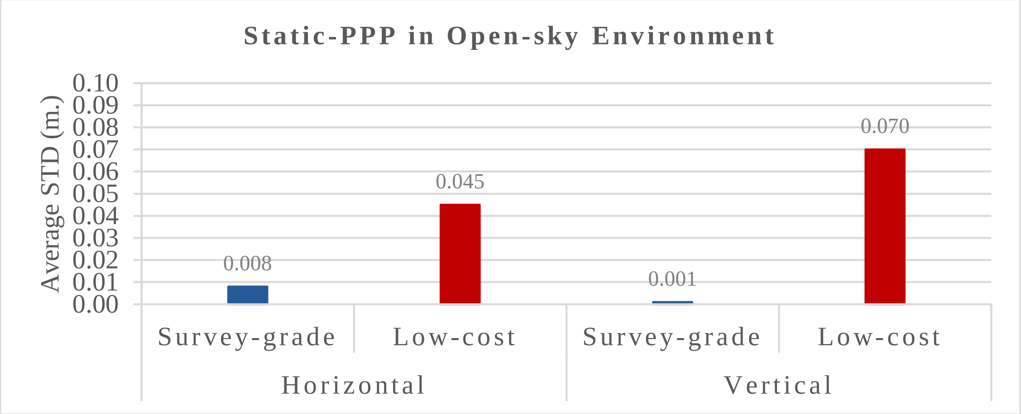

Figure 6: The average standard deviation in an open-sky environment

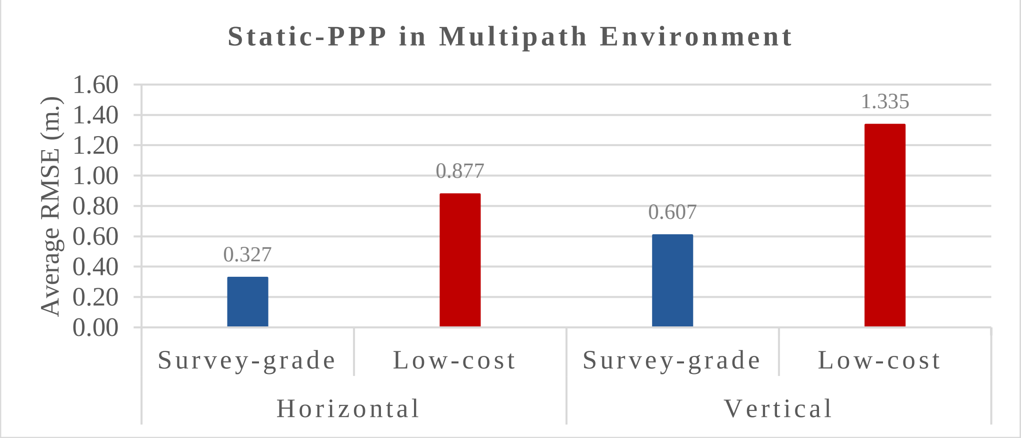

Figure 7: The average RMSE in a multipath environment

4.2 Kinematic Positioning Results

The kinematic test was conducted over approximately 4.5 kilometers, with receivers installed on a tricycle. The survey-grade receiver showed an average RMSE of 0.665 meters in the horizontal direction and 0.718 meters in the vertical direction. The results obtained from a low-cost receiver indicated that the average RMSE was 3.130 meters horizontally and 13.544 meters vertically (Figure 9). In Figure 10, the survey-grade provides 0.229 meters horizontally and 0.506 meters vertically for the standard deviation. A low-cost receiver provided 3.117 meters horizontally and 11.472 meters vertically.

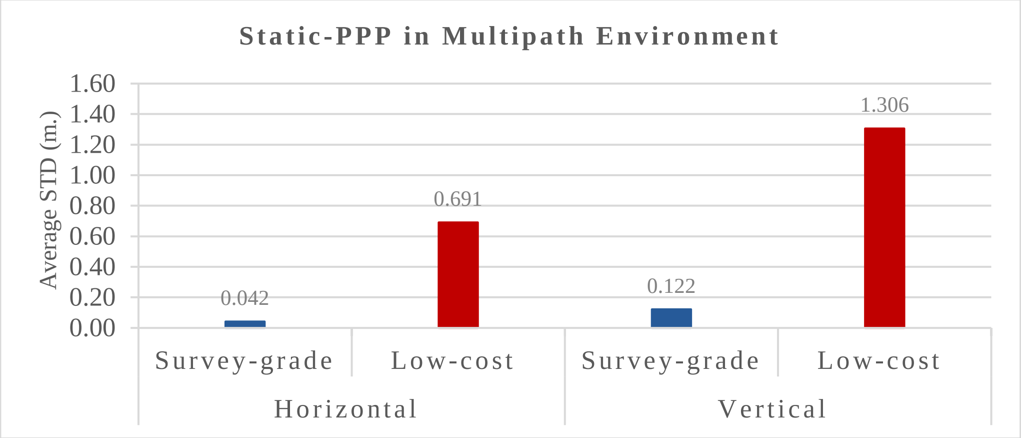

Figure 8: The average standard deviation in a multipath environment

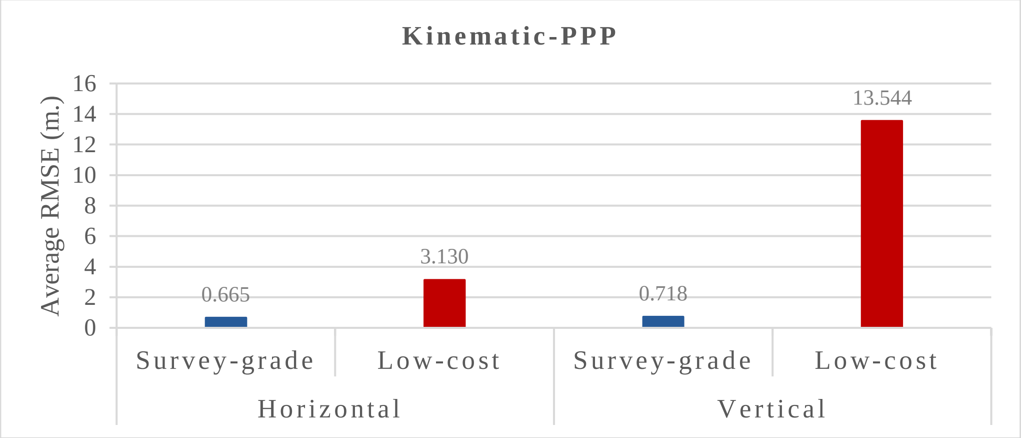

Figure 9: The average RMSE in kinematic positioning

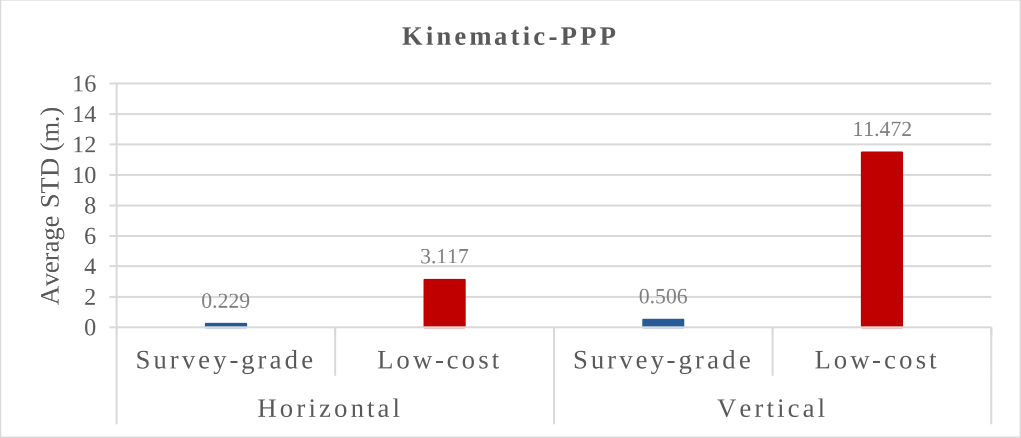

Figure 10: The average standard deviation in kinematic positioning

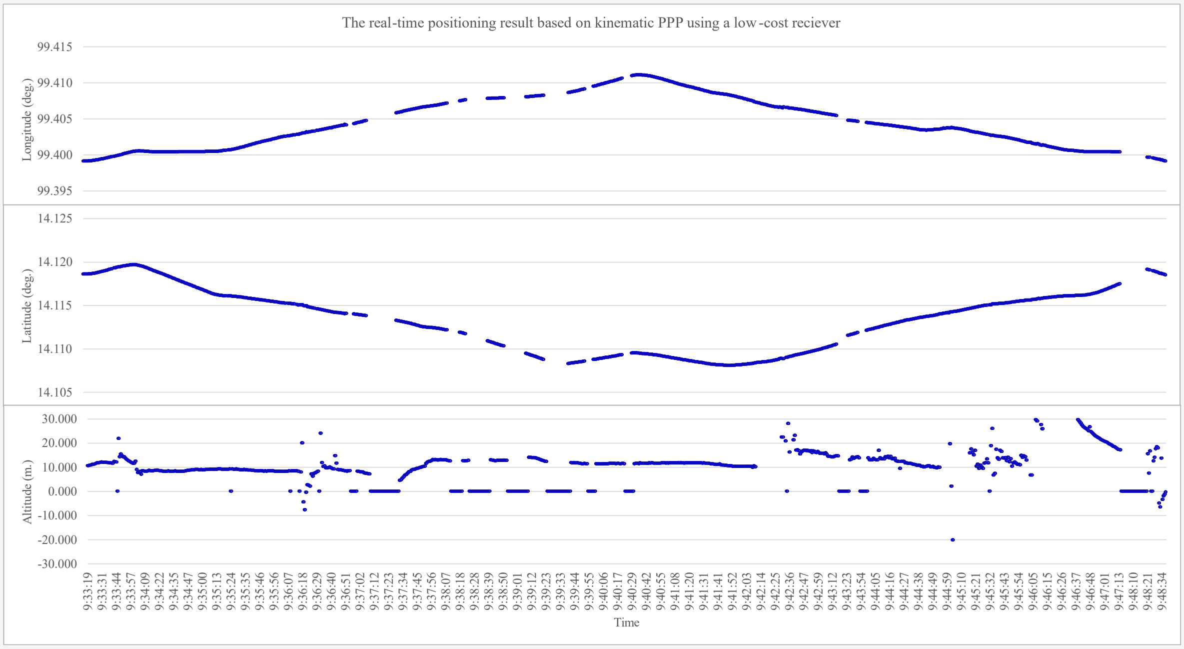

Figure 11: The positioning result in each epoch by kinematic-PPP based on a low-cost receiver

Table 3: The result of the positioning accuracy from all test scenarios

Test scenario	Type of receiver	Average RMSE (m.)		Average STD (m.)	
		Horizontal	Vertical	Horizontal	Vertical
Open-sky environment	Survey-grade	0.009	0.024	0.008	0.001
	Low-cost	0.060	0.072	0.045	0.070
Multipath environment	Survey-grade	0.327	0.607	0.042	0.122
	Low-cost	0.877	1.335	0.691	1.306
Kinematic test	Survey-grade	0.665	0.718	0.229	0.506
	Low-cost	3.130	13.544	3.117	11.472

In this scenario, the observations were promptly processed in real-time utilizing MADOCA corrections using the MADWIN software. Subsequently, post-processing kinematics was conducted using a nearby CORS station named ‘TKRI’ as a reference baseline. The survey-grade receiver provided an accurate positioning in both directions that was less than 50 centimeters. For a low-cost receiver result, the horizontal positioning error was approximately 3 meters. Unfortunately, in the vertical direction, the positioning error increased significantly to approximately 13 meters. There were two causes of this problem. Firstly, there needed to be more consistency in equipment installation due to the device's lack of anti-vibration protection equipment and its lightweight design. The second problem was that the road used in the test area contained numerous speed bumps. Figure 11 illustrates that these factors resulted in oscillation and cycle slips during signal reception, causing brief interruptions in the signal. Nevertheless, the temporary loss of signal did not impact the positioning errors in the horizontal direction, but it had a significant effect on the vertical direction, particularly during the first period when the signal was being received again.

Finally, all the positioning accuracy statistics mentioned above are shown in Table 3 for a convenient comparison

5. Conclusion

This study intended to evaluate the performance of utilizing MADOCA in precise point positioning with a low-cost GNSS receiver. The tests were performed using both static and kinematic approaches in different scenarios to assess the accuracy of positioning in both vertical and horizontal directions. The root mean square error (RMSE) was subsequently compared to the reference coordinates derived from the CSRS-PPP online processing service. In open-sky areas, the use of MADOCA with static positioning provided an average RMSE of 0.060 meters horizontally and 0.072 meters vertically.

Although there may have been some inconsistencies in accuracy compared to a survey-grade receiver, the overall level of accuracy remained satisfactory. When testing in a multipath scenario, the RMSE increased significantly to 0.877 meters horizontally and 1.335 meters vertically. Although the horizontal positioning accuracy is still centimeters (about half a meter), the vertical accuracy has fallen to almost a meter. This was caused by the various reflective surfaces and high-rise buildings that surround the location. This indicated a significant probability of receiving signals via multiple paths. Essentially, the most frequent error in carrier-phase tracking was caused by interference from a reflected signal equal to one-fourth of a wavelength (e.g. 4.76 centimeters for GPS L1). The cause was due to the instability of the equipment during vehicle testing. In addition, this problem can occur because of signal loss caused by the specific type of vehicle or the texture of the roadway's surface.

The kinematic PPP, with receivers mounted on a tricycle sidecar, achieved an average horizontal positioning accuracy of 3.130 meters. In comparison to the results from the survey grade receiver, the rise in error is about 2 meters, which was quite satisfactory. However, when measured vertically, the error increased dramatically to 13.544 meters, which is an increase from the survey grade of about 8 meters. The cause was due to three reasons: first, the instability of the equipment during vehicle testing, second, compact and lightweight antennas often have lower signal reception strength, multipath characteristics, and carrier phase center stability compared with surveying antennas. In addition, low-cost equipment faces a limitation in lack of anti-vibration protection. Last, signal loss was caused by the specific type of vehicle or the texture of the roadway's surface.

This study demonstrates the advantages of using MADOCA correction when used with a low-cost receiver for Precise Point Positioning (PPP). In addition to its acceptable positioning accuracy, it offers cost savings compared to a survey-grade receiver. In addition, the tool is compatible with usage in locations with limited internet access. While the processing program is user-friendly, there may be concerns over the careful installation of equipment and the appropriate length of time for receiving satellite signals. This is crucial for achieving positioning accuracy and precision in each task. The ongoing research needs to focus on testing in multiple scenarios to validate the utilization of MADOCA. Additionally, other base stations in various provinces of Thailand, apart from Chulalongkorn University, might be used. Nevertheless, this test involved obtaining correct information directly from the QZSS satellite system. This means it must use a MADOCA product in an alternative way, either through utilizing real-time processing with MADOCA correction obtained from the internet or by executing a post-processing using MADOCA correction values that are accessible on the website.

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