HEADING DETERMINATION ANALYSIS USING ORBIT AND TIME PRODUCTS FROM THE QUASI-ZENITH SATELLITE SYSTEM (QZSS): PRELIMINARY RESULTS

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ABSTRACT

The Quasi-Zenith Satellite System (QZSS) is a Global Navigation Satellite System (GNSS) technology owned by the Japanese government, with satellites orbiting and operating in Indonesian territory. Positioning activities using QZSS satellites employ the Real-Time Precise Point Positioning (RT-PPP) method to achieve precise positioning, correcting orbit, and clock errors directly from QZSS satellites. Currently, the Magellan System Japan (MSJ) receiver is equipped with the capability to receive precise orbit and clock corrections, enabling it to determine heading using QZSS satellites. This research aims to evaluate the precision of heading data estimated with precise clock and orbit corrections from QZSS satellites. To address this, we conducted heading data acquisition using static and kinematic MSJ receivers with precise orbit and clock corrections from QZSS. The heading data obtained from these methods were compared to data obtained using various other observation techniques, including static GNSS and real-time positioning with Omnistar correction, and total station measurements. Comparing the results of QZSS MADOCA (Multi-GNSS Advanced Data and Orbit Calculation), static GNSS, and total station static heading measurements revealed that the precision levels achieved by QZSS MADOCA measurements were higher when conducted over longer baselines. The highest precision value for QZSS MADOCA heading measurements was obtained with a 10-meter baseline, measuring at 0.014°, followed by measurements at 8 m, 2 m, and 1 m baselines, which yielded precision values of 0.016°, 0.058°, and 0.074°, respectively. Furthermore, the precision of QZSS MADOCA heading measurements compared to static GNSS reached 0.0004° for a 10-meter baseline. In the kinematic positioning, QZSS MADOCA heading values exhibited a precision range of 0.1658° to 1.1798° when compared to heading data obtained from Omnistar correction. In conclusion, the results indicate that heading determination using precise orbit and time corrections from QZSS MADOCA can be effectively utilized in hydrographic surveys.

***Key-words:** QZSS, Performance, RT-PPP, Indonesia, MADOCA, Correction*

1. INTRODUCTION

GNSS (Global Navigation Satellite System) technology has found widespread applications across various fields. GNSS-based positioning serves diverse purposes, encompassing agriculture, navigation, military operations, infrastructure development and monitoring, disaster mitigation, rehabilitation, and reconstruction, as well as regional and state boundary delineation, surveying, and mapping activities (Tariq et al., 2017).

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GNSS, satellite-based in nature, comprises one or more satellite constellations transmitting high-frequency radio signals that furnish time and location data to users globally, whenever needed. Several GNSS constellations are operational, including the United States's Global Positioning System (GPS), the European Union's Galileo, Russia's Global Orbiting Navigation System (GLONASS), China's Beidou Compass, India's Indian Regional Navigation Satellite System (IRNSS), and Japan's Quasi-Zenith Satellite System (QZSS) (Teunissen & Montenbruck, 2017). The QZSS satellite system operates regionally in the Asia Pacific Region, encompassing Indonesia.

On September 11, 2011, QZSS launched its inaugural satellite, named "Michibiki," which commenced full-scale operation in 2013. In 2017, three additional satellites were launched: two with Quasi-Zenith Satellite Orbits (QZO) and one with Geostationary Orbit (GEO). The QZSS satellite orbits in a distinctive figure-eight pattern, making it suitable for deployment in urban areas with numerous obstructions and regions with challenging topography (Teunissen & Montenbruck, 2017). Primarily, the QZSS augments the capabilities of GPS, addressing positioning and navigation challenges unattainable with GPS alone while enhancing measurement precision. QZSS satellites were originally designed by incorporating GPS navigation signals. Consequently, QZSS signals include L1C/A, L1C, L2C, L5, and L6, which are compatible with GPS signals. The L6 signal facilitates precise orbit and time corrections for the Real-Time Precise Point Positioning (RT-PPP) method. The L6 frequency band offers two correction services: MADOCA (Multi-GNSS Advanced Demonstration Tool for Orbit and Clock Analysis) for the L6E frequency band and CLAS (Centimeter Level Augmentation Service) for the L6D frequency band (Choy et al., 2015; Gumilar et al., 2021). Furthermore, CLAS can achieve centimeter-level accuracy in less than one minute. In contrast, MADOCA lacks the capability to provide propagation delay correction due to its less dense monitoring station coverage (Kobayashi, 2020). Consequently, the propagation delay correction is estimated by the receiver. This initial estimation process in the PPP method results in an initiation time from MADOCA, which typically takes around 20 to 40 minutes to attain centimeter accuracy (Namie & Kubo, 2020). Presently, CLAS coverage is limited to Japan, whereas MADOCA is available on a regional scale.

Several studies have been conducted on the accuracy of positioning using QZSS satellite in Indonesia, including works by Bramanto & Gumilar (2022) and Gumilar et al. (2021). Based on previous research, QZSS satellites have the potential to be used in surveying, mapping, and determining the heading of vessels. Heading data is crucial in hydrographic multibeam echosounder survey since it is used to calculate the positions of depth points along the swath area (Abdelsatar et al., 2024). A heading accuracy of less than 0.5° is required for all bathymetric survey orders based on IHO (International Hydrographic Organization) publication S-44 - Standard for Hydrographic Survey. Error of 0.5° in heading may lead to 1.5 meters of position error in the depth of 100 m at the swath width of 60° (IHO, 2020). Currently, GNSS satellites are frequently employed to ascertain vessel headings using various methods such as single point positioning (Ryu et al., 2016), integrated GPS and Inertia Navigation System (INS) (M. J. Choi et al., 2020), magnetometer and GPS (Henriksson, 2013), the relative differential method, the Differential Global Positioning System (DGPS) method (Felski & Mięsikowski, 1999), and the Precise Point Positioning (PPP) method (Specht et al., 2019). Specifically, regarding DGPS, it is a prevalent method used for determining the heading of vessels in survey operations. However, one significant drawback is the high subscription cost for correction services, which can be prohibitive for many users. In response to this challenge, the RT-PPP (Real-Time Precise Positioning Protocol) method that utilizes MADOCA corrections offers an alternative solution. This method allows for determining the heading of a vessel without incurring additional charges for corrections, making it more accessible (Suzuki, 2023). In addition to providing coordinates, the RT-PPP method with QZSS satellites can also supply vessel heading information via two antennas. Nonetheless, further research is needed to gauge QZSS performance in Indonesia concerning heading determination in navigation activities. This research aims to evaluate the performance of QZSS in Indonesia by examining heading measurements obtained using precise orbit and time corrections from MADOCA (hereafter QZSS MADOCA).

2. DATA AND METHODS

The PPP method is a precise absolute positioning technique that involves applying corrections to satellite clocks and orbits using a global data network station (Bulbul et al., 2021; B.-K. Choi et al., 2011; Gao, 2015). PPP employs carrier phase and pseudo-range measurements in an ionosphere-free linear combination (Abou-Galala et al., 2018; Bramanto et al., 2015; Xiang et al., 2017). Typically, the PPP method utilizes a single geodetic GNSS receiver, which simultaneously captures signals from multiple satellites. To determine the absolute position at a given epoch, four parameters are estimated: the receiver's position (N, E, U) and the receiver clock error (δt_r). Consequently, for absolute positioning tasks, a minimum of four satellites must be observed during a single epoch.

The RT-PPP method represents a real-time extension of the PPP method. Similar to the PPP method, RT-PPP is an absolute positioning approach that utilizes carrier phase and pseudo-range measurements to correct for ionospheric bias. In the RT-PPP method, an ionosphere-free (IF) linear combination is employed to mitigate the ionospheric delay, as described by equations (1) and (2) (Gumilar et al., 2021).

$$P_{IF} = \rho + T + c\left(\delta t_r - \delta t_s \right) + \left(b_{r,IF} - b_{IF}^{S}\right) + \varepsilon_{IF} \quad (1)$$

$$\Phi_{IF} = \rho + T + N_{IF} + c(\delta t_r - \delta t_s) + \left(\varphi_{r,IF} - \varphi_{IF}^{S}\right) + \varepsilon_{IF} \quad (2)$$

where P_{IF} and Φ_{IF} are the pseudorange and carrier phase IF codes, while Pi and Φi (with a value of i = 1.2) represent the magnitudes of the carrier phase. ρ stands for the geometric distance, T denotes the tropospheric delay, δt_r and δt_srefer to the time errors of the receiver and satellite, c represents the speed of light in a vacuum, $b_{r,IF}$ and b_{IF}^{S} represent device delays from the receiver and satellite, $\varphi_{r,IF}$ and φ_{IF}^{S} indicate uncalibrated phase lags, N_{IF} denotes the carrier phase ambiguity of the IF, measured in units of length, and ε_{IF} stands for the amount of noise.

The fundamental difference between the PPP and the RT-PPP methods is that RT-PPP can provide precise position information with real-time corrections without the need for any post-processing. GNSS RT-PPP technology achieves high accuracy without the data differencing process between the base and rover, thanks to its use of a global Continuously Operating Reference Station (CORS) network. This network calculates precise satellite orbit corrections and satellite clocks. As a result, RT-PPP is claimed to be capable of delivering horizontal position accuracy as fine as 10 cm, with an initialization time of 15-20 minutes. The required satellite orbit and clock information is transmitted via L-band signals to geostationary satellites, which then relay it to the receiver (Shi et al., 2014; Zhang et al., 2019). The RT-PPP method relies on a GNSS receiver equipped with L-band signal capture. This L-band signal capture enables GNSS receivers to receive corrections from communication satellites that have received broadcast ephemeris corrections from navigation satellites. However, it is worth noting that the RT-PPP method is heavily reliant on corrections from communication satellites and is susceptible to potential obstructions (Alkan et al., 2020; Erol et al., 2020). In contrast, the PPP method necessitates high-precision orbit $(d\rho)$ and time data (δt_s), which can be downloaded from the International GNSS Service (IGS) for accurate positioning. Meanwhile, RT-PPP receives orbit $(d\rho)$ and time (δt_s) corrections from the Satellite Based Augmentation System (SBAS), which are computed from the reference system (Bramanto et al., 2015; Jin et al., 2021).

A heading represents the direction indicated by a tool or container in positioning and navigation activities at a specific time. It is the relative angular distance to the north, typically measured clockwise from 0° north. The heading value changes as the vehicle moves or changes position. Various types and methods exist for determining heading values, including velocity heading, magnetic heading, gyro compass heading, acoustic heading, and dual antenna heading (Gade, 2016; King & Cooper, 1993; Schnaufer et al., 2016). In this study, the heading value was determined using the dual antenna heading method, with the estimated heading value calculated from the relative heading angle values of the reference station and one rover station position, employing the following equation:

$$\alpha_{AB} = Tan^{-1}\left[\frac{E_B - E_A}{N_B - N_A}\right] \tag{3}$$

where E_A and N_A represent the easting and northing coordinates of the reference station, E_B and N_B denote the easting and northing coordinates of the rover station, with α_{AB} representing the directional angle value.

In this research, heading values are estimated using MADOCA, RT-PPP, static GNSS, and total station techniques. The research locations are divided into two areas (see **Fig. 1**): Bandung for testing heading precision, and the Kepulauan Seribu near Jakarta for experiments on determining heading in the waters. The selection of these two locations is primarily based on their proximity to our base. The determination of heading values through QZSS MADOCA and RT-PPP is carried out in real-time by calculating the relative azimuth angles between the reference and rover station position. The reference station provides Real-Time Correction Messages (RTCM) corrections to the rover station, subsequently computing the heading solution and transmitting it back to the reference station. Meanwhile, heading values derived from static GNSS and total stations are obtained by calculating relative azimuth angles from the coordinates of the reference and rover station as measured using static GNSS and total station.

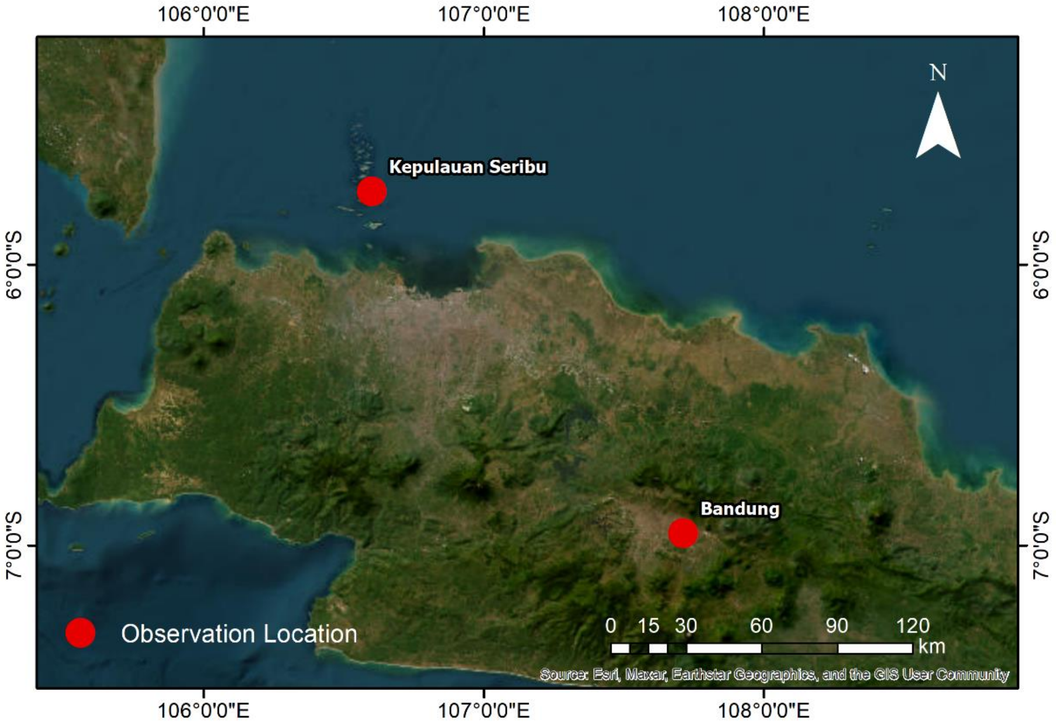

Fig. 1. Research locations: Bandung for heading precision testing and Kepulauan Seribu near Jakarta for heading determination in waters.

The data for this research is collected from acquisitions at the Gelora Bandung Lautan Api Stadium (see **Fig. 2**). The acquired data includes heading comparison data utilizing corrections from the QZSS MADOCA, static GNSS, and total station measurements. Subsequently, the heading values from real-time QZSS MADOCA, static GNSS, and total station are compared, with the duration and positions of measurement points standardized to predetermined baselines (1, 2, 8, and 10 meters from the reference station).

Fig. 2. The acquisition locations at Gelora Bandung Lautan Api Stadium.

The selection of baseline length takes into account practical measurements, generally in surveys conducted in water, where the minimum baseline distance is 1 meter, as indicated by the Veripos equipment. This analysis aims to assess the impact of baseline length on the quality of static heading data. The heading values obtained from static GNSS, and total station measurements serve as the reference for evaluating the heading values obtained from QZSS MADOCA. In the measurements employing a total station, the coordinates of the standing point and backsight point are initially acquired using static GNSS measurements tied to CORS ITB, with an observation time of 30 minutes. The distance from CORS ITB to the observation location is less than 10 km, with a precision level of 3-5 mm. We believe that this duration of observation is sufficient for heading measurements. Additionally, the data utilized include both GPS and QZSS, with a mask angle of 15 degrees and a 1-second interval.

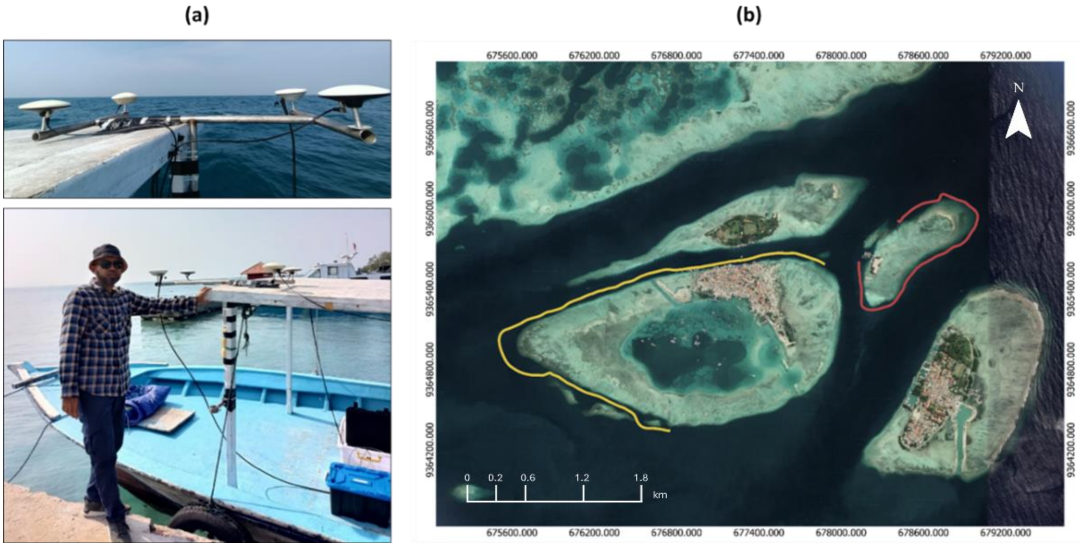

Fig. 3. Overview of (a) the positions of each antenna and (b) the vessel's track (the map uses the Universal Transverse Mercator (UTM) Projection System, Zone 48S). The yellow track represents measurements taken over 25 minutes, and the red track represents measurements taken over 15 minutes.

Measurements at sea were conducted to validate the simulation results obtained on land and assess the potential use of QZSS satellites for determining heading in hydrographic surveys. These measurements were carried out in the waters of Kepulauan Seribu, Jakarta, Indonesia, utilizing a heading comparator from a Trimble receiver with Omnistar correction. In the official brochure, it specifies that the accuracy of the Trimble Omnistar is between 0.05° and 0.09° (Omnistar, 2024). **Fig. 3** provides an overview of the positions of each antenna and the vessel's track.

3. RESULTS AND DISCUSSION

The objective of this analysis is to assess the impact of baseline length on the quality of static heading data by comparing the precision levels of heading values obtained from QZSS MADOCA, static GNSS, and total station. These findings are instrumental for planning antenna placement on vessels during hydrographic measurements. **Fig. 4** shows the histogram graph and the rose plot of heading data from QZSS MADOCA for 1 m, 2 m, 8 m, and 10 m baselines. The histogram graph demonstrates that the highest precision for QZSS MADOCA heading was achieved with a 10 m baseline at 0.014°, followed by baselines of 8 m, 2 m, and 1 m, with values of 0.016°, 0.058°, and 0.074°, respectively. These results also illustrate that longer baselines result in smaller standard deviation values for QZSS MADOCA heading, this finding is consistent with what was discussed by (Medina et al., 2018). However, it is important to adjust these results to suit specific survey needs and vessel geometry.

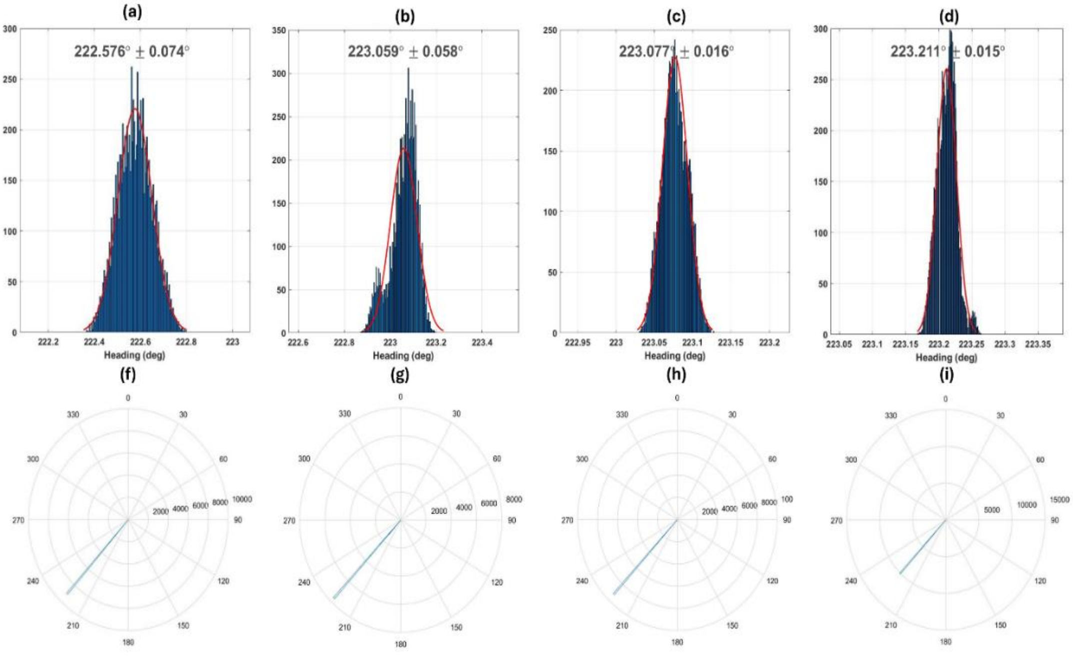

Fig. 4. The histogram graph of heading values for (a) 1 m, (b) 2 m, (c) 8 m, and (d) 10 m baselines, along with a rose plot of heading values for (e) 1 m, (f) 2 m, (g) 8 m, and (h) 10 m baselines from QZSS MADOCA.

Fig. 5 presents a comparative graph of QZSS MADOCA, static GNSS, and total station heading values over time for 1 m, 2 m, 8 m, and 10 m baselines. The graphs reveal that for measurements with longer baselines, the heading values from QZSS MADOCA closely align with those from static GNSS and total station. However, the heading values from the total station exhibit a notable difference compared to the other two methods, potentially due to measurement errors such as centering, leveling, or targeting inaccuracies. Static GNSS heading values are used as the validation source, given their minimal systematic errors. The heading precision for the 1 m, 2 m, 8 m, and 10 m baselines is 0.022°, 0.013°, 0.013°, and 0.0004°, respectively. In addition, in practice, adjustments must still be made according to the size and situation of the vessel, as well as the precision required for the task at hand.

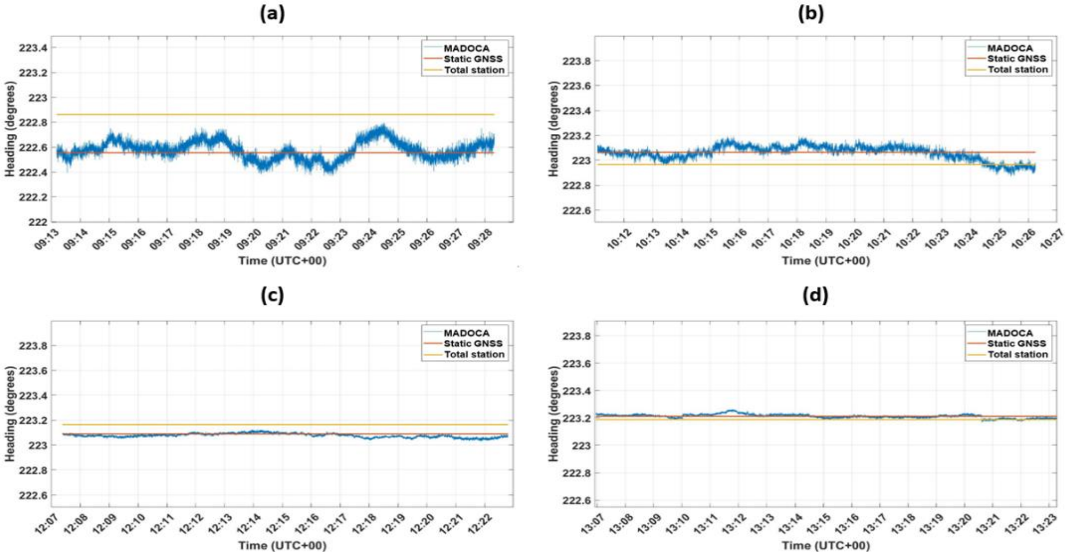

Fig. 5. Comparison of QZSS MADOCA, static GNSS, and total station heading values against time for (a) 1 m, (b) 2 m, (c) 8 m, and (d) 10 m baselines.

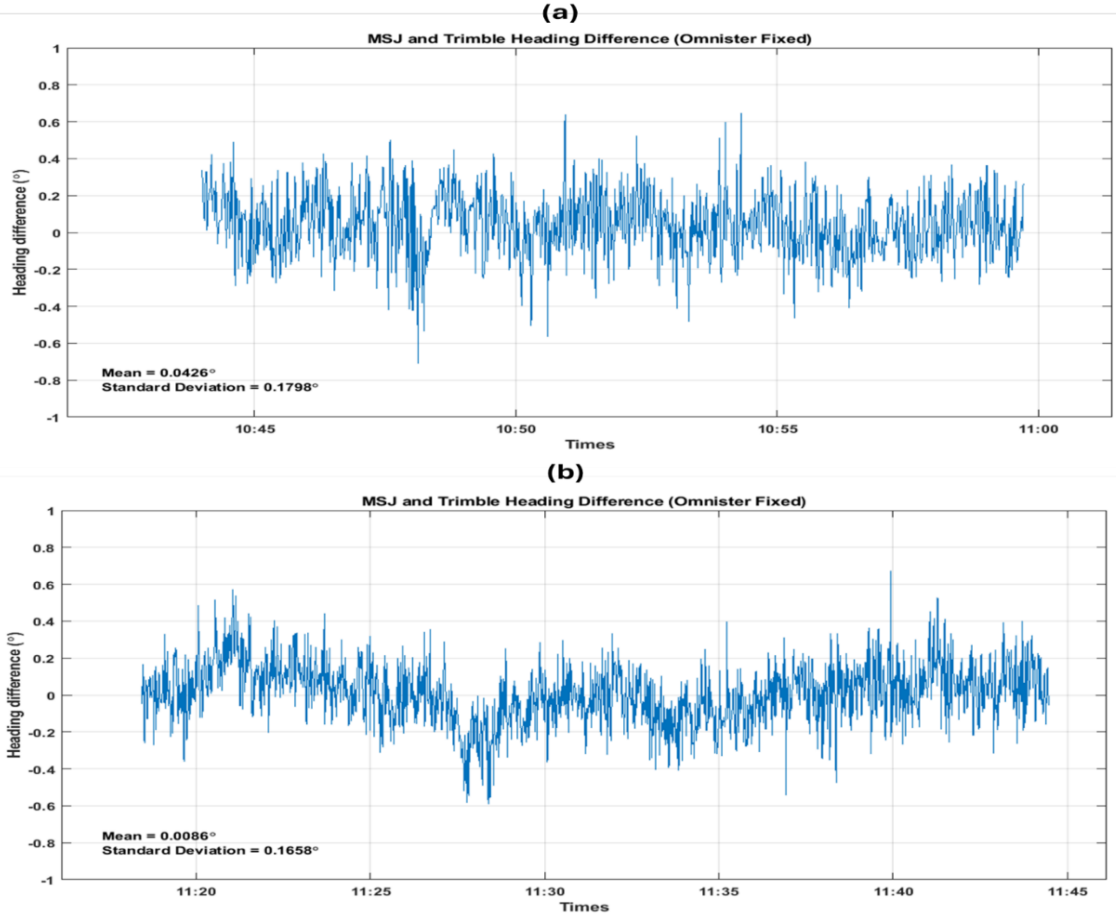

Fig. 6. Difference in QZSS MADOCA and RT-PPP heading measurement trajectory plots measured over (a) 15 and (b) 25 minutes.

The results of determining vessel heading using the QZSS satellite with Omnistar correction in hydrographic surveys in the Kepulauan Seribu are depicted in **Fig. 6**. The heading from the Trimble Omnistar, considered accurate, has a standard deviation of 0.09°. In contrast, the standard deviation for vessel heading using QZSS is 0.17°. Therefore, determining vessel heading using the QZSS satellite is a viable option for hydrographic surveys since the Standard for Hydrographic Surveyor S-44 IHO requires a maximum of 0.5° accuracy of heading measurements (IHO, 2020). **Fig. 7** shows the effect of 0.17° heading error on position at several depths and swath angles of the hydrographic multibeam survey. On the depth of 40 m in 60° of swath angle, the position error will be 0.21 m, which fulfills the position accuracy even for the special order of hydrographic survey in the S-44 IHO (1 m).

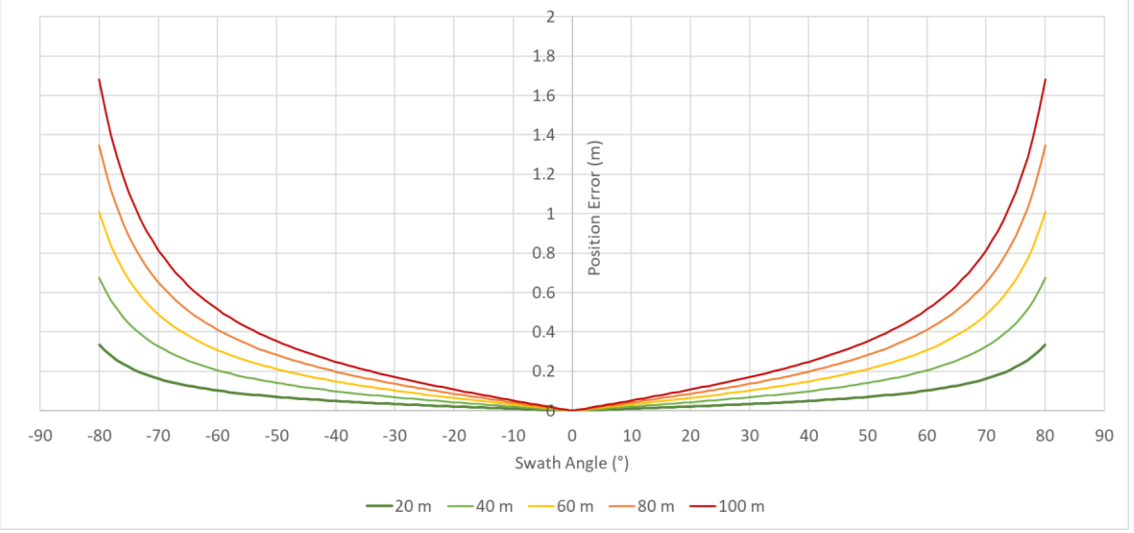

Fig. 7. Error of depth point position as an impact of 0.17° heading error at several depth (20-80 meters) and several swath-angles (0°-80°).

4. CONCLUSIONS

The comparative results of QZSS MADOCA, GNSS, and total station for static heading measurements demonstrate that the precision of QZSS MADOCA increases with longer baselines. The highest precision is attained with a 10 m baseline, measuring 0.014°, followed by baselines of 8 m, 2 m, and 1 m, with precision values of 0.016°, 0.058°, and 0.074°, respectively. The results of the heading value comparisons between QZSS MADOCA and static GNSS indicate that the smallest difference in heading values is observed in measurements with a 10 m baseline. Furthermore, the precision of heading values from QZSS MADOCA, in comparison to static GNSS, reaches 0.0004° for a 10 m baseline. These findings reveal a clear pattern and lead to the conclusion that the length of the baseline significantly influences the precision of resulting heading data, with longer baselines resulting in more accurate heading values. However, in practice, it should be adjusted according to the size and situation of the vessel, as well as the precision required for the task at hand.

For kinematic heading measurements, QZSS MADOCA provides heading precision ranging from 0.1658° to 1.1798° compared to heading obtained from Omnistar correction. Consequently, it can be concluded that determining vessel heading using precise orbit and time corrections from QZSS MADOCA is a viable option for hydrographic surveys. Expanding the research area to examine the consistency of the obtained heading will be essential for future studies. Additionally, further research is needed on the application of QZSS MADOCA in terrestrial areas with significant obstructions that may interfere with signal propagation.

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