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Experimental Results of Ship's Maneuvering Test Using GPS

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Abstract : *The Kinematic GPS is well known to provide a quite good accuracy of positioning within cm level. Although kinematic GPS assures high precision measurement on the basis of an appreciable distance between a reference station and an observational point, it has measurable distance restriction within 20 km from a reference station on land. Therefore, it is necessary to make out a simple and low-cost method to obtain accurate positioning information without distance restriction. In this paper, the velocity integration method to get the precise velocity information of a ship is explained. The experimental results of Zig-zag maneuver and Williamson turn as the ship's maneuvering test, and other experimental results of ship's movement during leaving and entering the port with low speed were shown. From the experimental results, ship's course, speed and position are compared with those obtained by kinematic-GPS, velocity integration method and dead reckoning position using Gyro-compass and Doppler-log.*

Key words : *Williamson turn, Zig-zag maneuver, kinematic GPS, carrier-phase-derived Doppler measurement, velocity integration method, dead reckoning position*

1. Introduction

It is well known that the Kinematic GPS (K-GPS) provides accurate positions within *cm* level. Although K-GPS assures precise measurement accuracy in *cm* order on the basis of an appreciable distance between a reference station and an observational point, it has intrinsic disadvantage that a reference station on land is required, and the distance between the reference station point and the observational point is limited within 20 km. Therefore, in the case of using it at sea, it is necessary to make out a simple and low-cost method to obtain accurate positioning information.

The velocity of a movable body can be easily determined by using the GPS receiver generated Doppler measurement or the carrier-phase-derived Doppler measurement as long as the satellite velocity is precisely known. The Doppler measurement generated by GPS receiver is a measure of instantaneous velocity that is measured over a very short time interval, whereas the carrier-phase-derived Doppler measurement is a measure of mean velocity between observation epochs. The velocity integration with respect to time is the displacement during a period between the two epochs. In the previous 2005 ANC (Asia Navigation Conference) at Dalian, on the basis of the experimental results using five buoys at sea, some comparative results between the point positioning by the velocity integration method (VI-GPS) and the position by K-GPS were shown, respectively. From the experimental results, the 3 dimensional displacements of movable body by VI-GPS could be obtained accurately in the high frequency components over 0.07 Hz (Hou, 2005).

In this research, a method for the velocity measurement using VI-GPS is described, and two kinds of experiments, which are the ship's maneuvering test (Zig-zag maneuver, Williamson turn) and the speed, trail comparison during leaving and entering the port, were carried out to evaluate the accuracy of K-GPS and VI-GPS. The experimental results from K-GPS and VI-GPS have been compared with the result from the Dead Reckoning Position (DRP) by Gyro-compass and Doppler-log. In both experiments, four GPS receivers were set up on the training ship Fukaemaru and the reference station was placed within a distance of few km apart from the training ship's position. In the first experiment, two maneuvering tests (Williamson turn and Zig-zag maneuver) were conducted and the experimental results were used to compare the speed and trail by VI-GPS, K-GPS and DRP. In the second experiment, during entering and leaving the port, the data from each GPS receiver was used to calculate the ship's 3 dimensional movements with low speed, and the data of four GPS receivers on the training ship were compared with the results by DRP.

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2. Velocity Integration Method

The observation equation for the GPS carrier phase measurement is as follows (Hou, 2006):

$$\Phi = \rho + c \cdot (dt - dT) + \lambda N - d_{ion} + d_{trop} + \varepsilon_{\Phi} \quad (1)$$

Time differential observations are obtained by subtracting the observations at the previous epoch k-1 from those at the present epoch k. When the interval of observations is short, it is assumed that variations of propagation errors in the ionosphere and troposphere are small and negligible. The time differential observation is expressed in the following equation and temporal differences remove the phase ambiguities.

$$\delta\Phi = \delta\rho + c \cdot (\delta dt - \delta dT) + \varepsilon_{\delta\Phi} \quad (2)$$

where ρ is the distance between satellite and receiver (m); $c$isthelightvelocityinvacuum(m/s); Φ is the carrier phase measurement (m); λ is the carrier wavelength (m); Nistheintegercarrierphaseambiguity(cycles); d_{ion} is the bias of the ionospheric delay (m); d_{trop} is the bias of the tropospheric delay (m); dt is the bias of the satellite clock (s); dT is the bias of the receiver clock(s); $\delta\Phi$ is the phase observation in temporal difference between two epochs (m); δdt is the variation of the satellite clock errors (s); δdT is the variation of the receiver clock errors (s); $\varepsilon_{(*)}$ is the measurement noise and the errors which cannot be modeled, and the symbol δ is the time differential operator.

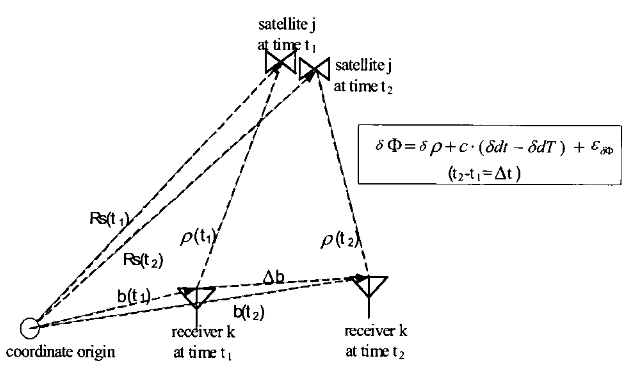

Fig. 1 Time differential carrier phase measurement by VI-GPS

Observations at 1 second interval give a solution for unit displacement, *i.e.*, velocity. Fig.1 shows the time differential carrier phase measurement by VI-GPS.

3. Experiment

3.1 Outline of Experiment

The experiment was carried out on April 8th of 2005 in the coastal area of Kobe, Japan. Four antennas equipped with K-GPS were installed on bow, stern and both sides of Fukaemaru training ship, as shown in Fig. 2. The reference station for K-GPS was installed on the breakwater of Faculty of Maritime Sciences pond of Kobe University as shown in Fig. 3. The observations were done during navigation, leaving and entering the port, and the experimental site for ship's maneuvering test is shown in Fig.4. The data of ship motion by GPS system was analyzed and compared with the traditional measurement results of DRP. During navigation, Zig-zag maneuver and Williamson turn were conducted. The ship handling maneuverability indices T (yaw quick responsibility and course stability index), K (steady turning ability index) obtained by Gyro-compass, Doppler-log, K-GPS and velocity integration method were compared each other, also the trail and the speed results were compared. Here, T and K are generally used in the first order approximation formula of turning movement, and are expressed as following equation:

$$T\frac{d\dot{\psi}(t)}{dt} + \dot{\psi}(t) = K \cdot D(t) \quad (3)$$

where $\psi(t)$ is turning angle (deg), $\dot{\psi}(t)$ is turning angular velocity (deg/s), $d\dot{\psi}(t)/_{dt}$ is turning angular acceleration (deg/s^2)and $D(t)$ is rudder angle (deg).

During leaving and entering the port, the course and the speed obtained by VI-GPS and K-GPS were compared with the Gyro-compass course and the Doppler-log speed. The K-GPS receivers measured the 3 dimensional movements (latitudinal, longitudinal and vertical) of the ship relative to the reference station with 5 Hz of sampling frequency. The data of K-GPS was recorded in the PDA (Personal Digital Assistant) during navigation, leaving and entering the port, and compared with the results of DRP and VI-GPS.

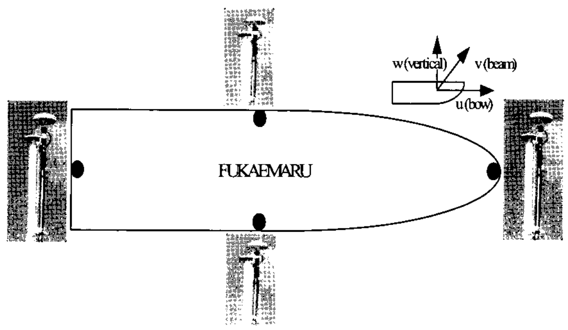

Fig. 2 GPS antenna positions on Fukaemaru training ship

Fig. 3 Reference station on break water

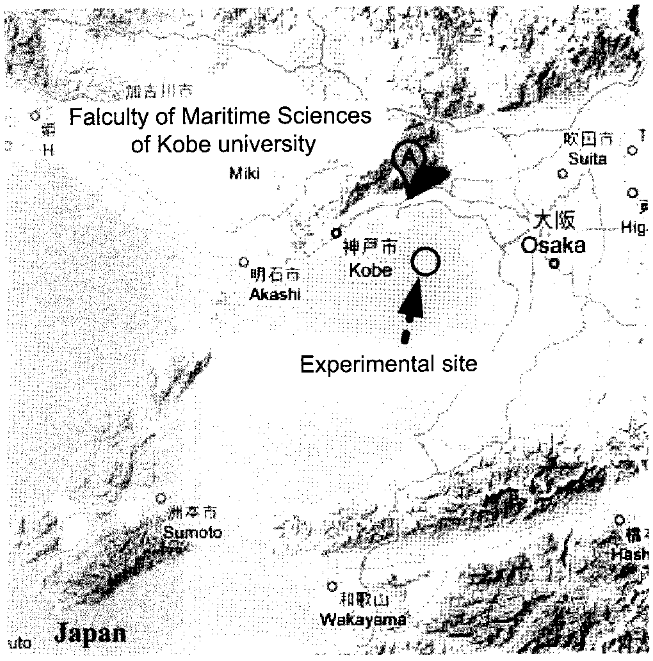

Fig. 4 Experimental site of ship's maneuvering test

3.2 Experimental Results

1) Ship's Maneuvering Test

During navigation, Zig-zag maneuver and Williamson turn were performed to measure the ship's maneuvering characteristics, and the ship's handling maneuverability indices were compared each other. Zig-zag maneuver was conducted with zero rudder achieving steady speed for a while and deflected the rudder to starboard 10°, and held until the vessel turns to starboard 10°. Then deflected the rudder to port 10°, and held until the vessel turns to port 10° with respect to the starting heading. The comparison results of trail and speed by K-GPS, VI-GPS and DRP during Zig-zag maneuver and Williamson turn were shown Figs. 5 to 8.

Figs. 5 and 6 show the trail results during Williamson turn and Zig-zag maneuver by K-GPS with black dot line, VI-GPS with block line and DRP with gray line. From the trail comparison results, there is a big difference between two GPS results (K-GPS, VI-GPS) and DRP trail. The trail delay of DRP becomes large in Williamson turn and Zig-zag maneuver compared with the trail results by K-GPS and VI-GPS. As shown in Figs. 5 and 6, because the two results of K-GPS and VI-GPS have a good correspondence, the trails by K-GPS and VI-GPS look as one line, and there is a small difference of maximum 1.4 m in the results of Williamson turn. However, DRP trail shows some delay compared to the results of K-GPS and VI-GPS, and it becomes large in Williamson turn and Zig-zag maneuver with maximum 50 m.

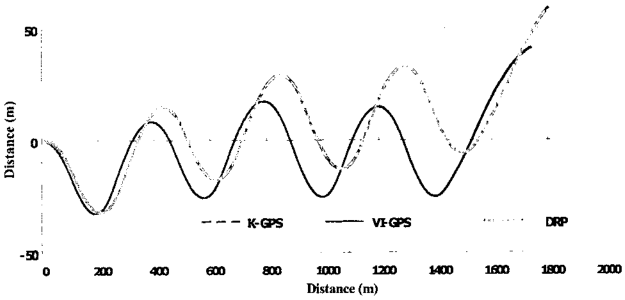

Fig. 5 Trail comparison during Zig-zag maneuver

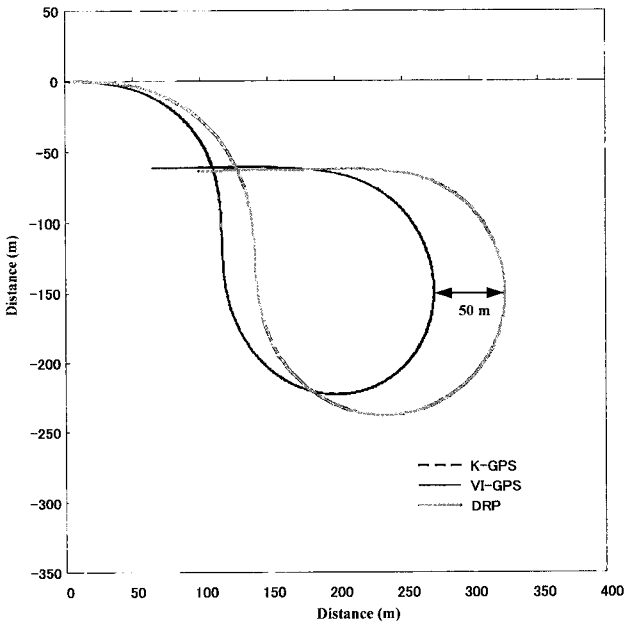

Fig. 6 Trail comparison during Williamson turn

To find out the reason of delay, the speed results compared with K-GPS, VI-GPS and Doppler-log are shown in Figs. 7 and 8. The Log speed was collected by the data recording system of Fukaemaru, and the speed of K-GPS and VI-GPS was calculated from the mean value of four antennas installed on the ship. Figs. 7 and 8 show the speed during Zig-zag maneuver and Williamson turn, respectively.

The speed results by K-GPS and VI-GPS show a good correspondence in both of bow and beam directions as shown. However, the speed by Doppler-log shows a delay compared with the results by K-GPS and VI-GPS, and it becomes large in Williamson turn with 17 seconds of maximum delay. From the above results, it is clear that there is a time delay of DRP compared to K-GPS and VI-GPS. Especially from the result of Williamson turn, it makes out that Doppler-log has some delay of tracking according to the speed changes that ship operates with same speed under the speed down situation for the maneuvering test during navigation.

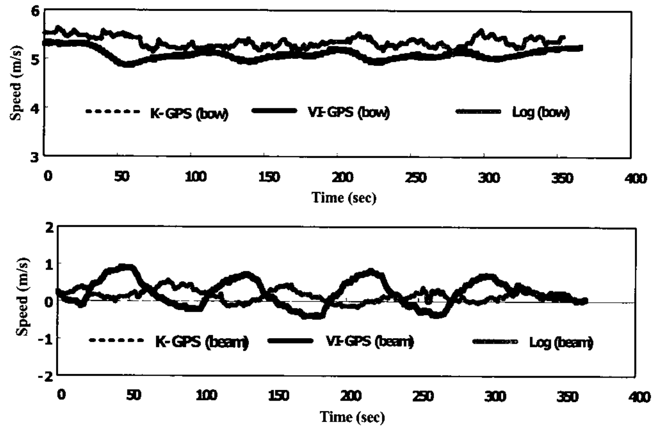

Fig. 7 Speed comparison during Zig-zag maneuver (upper shows in bow direction, lower in beam direction)

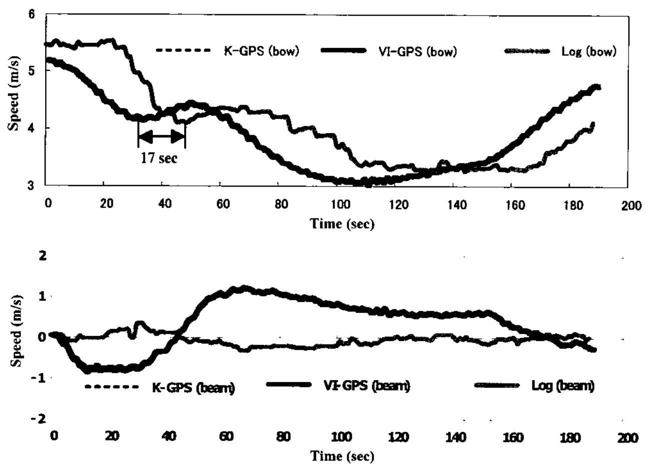

Fig. 8 Speed comparison during Williamson turn (upper shows in bow direction, lower in beam direction)

Table 1 shows the ship handling maneuverability indices T (sec) and K (1/sec) obtained from Zig-zag maneuver results. Here, T' and K' show the dimensionless indices of T and K which are T'=T*(V/L) and K'=K/(V/L), where V (m/s) is the ship speed and L (m) is the length of ship (Honda, 2001).

Table 1 Ship handling Maneuverability indices T, K

	T (sec)	K (1/sec)	T'	K'
K-GPS	19.25	0.17	2.27	1.45
VI-GPS	19.33	0.17	2.28	1.45
DRP	19.69	0.15	2.42	1.18

(T', K' are the dimensionless indices of T, K.)

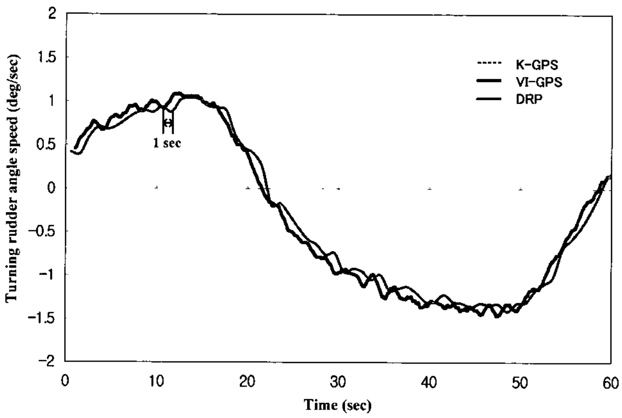

Fig. 9 Turning rudder angle speed during Zig-zag maneuver

Particularly, it is considered that the index T depends on the time delay of Gyro-compass mainly, and the index K depends on the time delay of Gyro-compass and Doppler-log intricately (Nakama, 2005). The results of K-GPS and VI-GPS show almost same value in maneuverability indices, but the maneuverability indices of DRP were slightly different from K-GPS and VI-GPS. Turning rudder angle speed is shown to examine the reason that DRP has different indices of T, K by K-GPS and VI-GPS. From the results of Fig. 9, it is known that DRP has 1 second delay compared to K-GPS and VI-GPS, and its peak value is smaller than the others. This could be the reason that DRP indices are different with those of K-GPS and VI-GPS, because it would take more time to start turning at that moment and it has lower value of peak.

2) Leaving and Entering Port

The trail and speed by K-GPS, VI-GPS and DRP during leaving and entering the port are compared each other. Figs. 10 and 11 show the trails by K-GPS with block line, VI-GPS with blue line and DRP with red line during leaving and entering the port. From the result of Fig. 10, VI-GPS shows a similar trail with K-GPS until around 100 seconds, but it becomes different during backward motion and the trail difference between K-GPS becomes large when the ship moves forward with low speed in the harbor. The trail by DRP also shows a different result with K-GPS, but the two trails become similar gradually from around 240 seconds. Fig.11 shows the trail comparison results during entering port, and the three trails by K-GPS, VI-GPS and DRP are similar until around 240 seconds, but VI-GPS trail becomes different according to speed down in the harbor and DRP trail is similar with K-GPS trail, but the final berthing position is slightly different with the position by K-GPS.

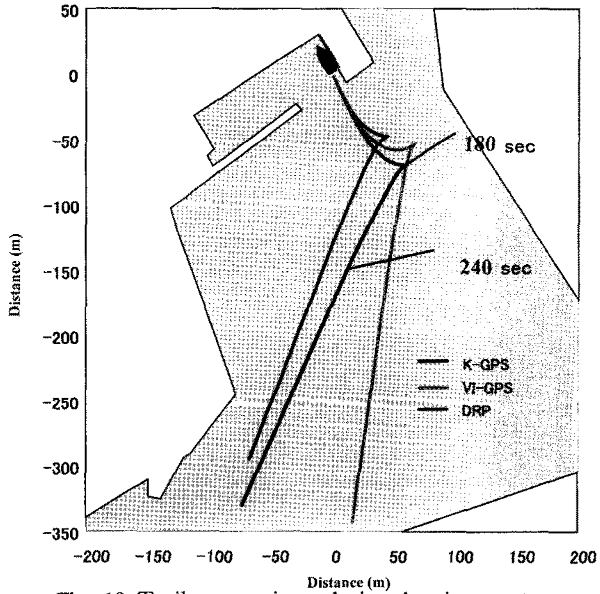

Fig. 10 Trail comparison during leaving port

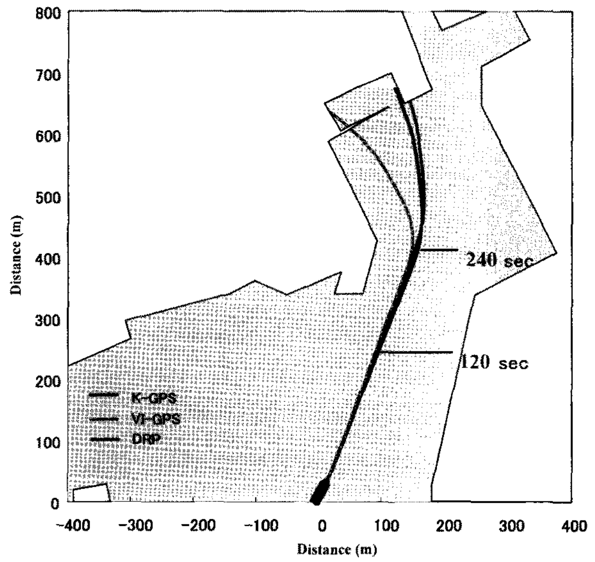

Fig. 11 Trail comparison during entering port

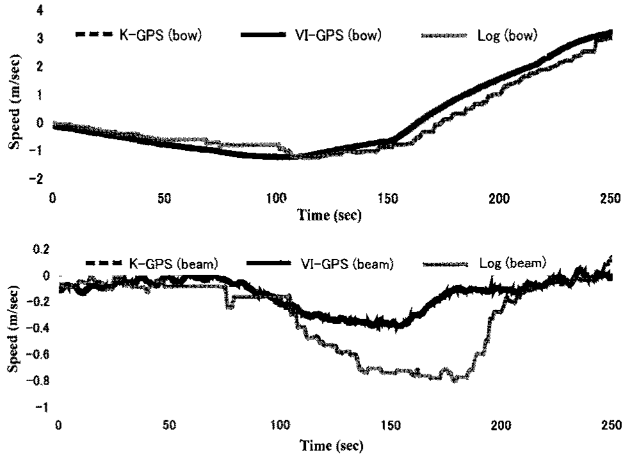

Fig. 12 Speed comparison during leaving port (upper shows in bow direction, lower in beam direction)

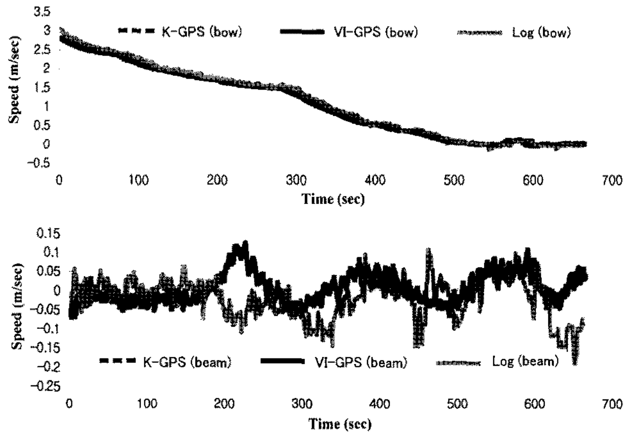

Fig. 13 Speed comparison during entering port (upper shows in bow direction, lower in beam direction)

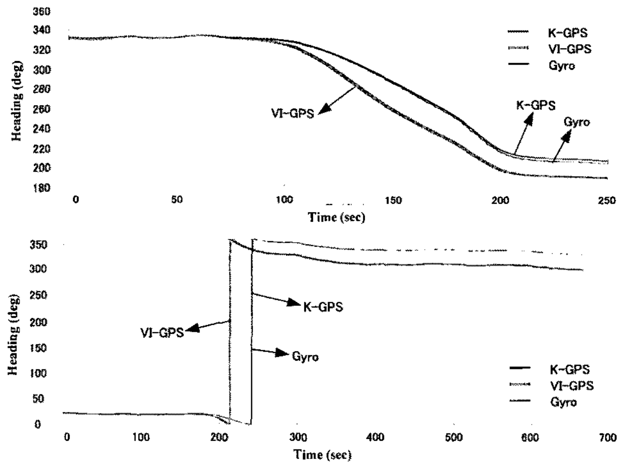

Fig. 14 Ship heading during leaving and entering port (upper shows leaving port, lower shows entering port)

In order to find out the reason that VI-GPS has different trail with K-GPS, the speed comparison results by K-GPS, VI-GPS and Doppler-log are shown in Figs. 12 and 13, also the ship heading comparison results by Gyro-compass are shown in Fig. 14. Figs. 12 and 13 show the speed results of K-GPS, VI-GPS and DRP in bow and beam directions during leaving and entering the port. As shown in Figs.12 and 13, K-GPS and VI-GPS show a good correspondence in both cases of leaving and entering the port, but the result of Doppler-log shows some delay compared to GPS results. The speed error between K-GPS and VI-GPS showed 0.055 m/s of maximum error. Fig. 14 shows the ship heading comparison results by K-GPS with block line, VI-GPS with gray line and Gyro-compass with red line. From the results, the ship headings by K-GPS and Gyro-compass show a good correspondence, but VI-GPS shows different heading results in both of leaving and entering the port.

From these results, it is known that the speed information of VI-GPS has a quite good accuracy compared to K-GPS. The trail difference between K-GPS and VI-GPS is not for the velocity information by VI-GPS but for the integral error according to time proceeding with low speed in the harbor for the berthing situation.

3.3 Considerations

From the results of ship's maneuvering test, the ship's trail by DRP showed a delay, and the ship's velocity by Doppler-log also showed some time delay compared to the results by K-GPS and VI-GPS. Also, from the results of leaving and entering the port, the speed by K-GPS and VI-GPS showed a good correspondence each other, but the Doppler-log speed showed a time delay compared to GPS results.

From the results of Figs. 10 to 14, the trail difference between DRP and K-GPS is considered due to the time delay of speed by Doppler-log. The trail difference between K-GPS and VI-GPS is considered due to the integral error according to the time proceeding especially with low speed in the harbor for berthing as shown in Fig. 14, and it is not for the velocity information of VI-GPS as shown in Figs. 12 and 13.

As long as the measurement could be done with comparatively high speed (not leaving and entering the port situation), the results of trail and speed by K-GPS and VI-GPS were almost same. However, as the measurement time was increased with low speed for the berthing situation, the integral error by VI-GPS was increased and showed a delay in trail compared to the results by Gyro-compass and K-GPS. Although VI-GPS has the integral error mainly in the low speed, as VI-GPS is not needed a reference station on land, it is one of the useful measurement methods of a movable body at sea.

4. Conclusion

In this study, we carried out the experiments during navigation, leaving and entering the port to evaluate the accuracy of VI-GPS, and compared with the conventional method using DRP (Dead Reckoning Position) and K-GPS. The Zig-zag maneuver and Williamson turn were done during navigation, and the ship trail and speed by K-GPS, VI-GPS and DRP were compared each other. There is no difference in ship trail and speed results between K-GPS and VI-GPS during navigation, but the DRP showed a time delay compared to K-GPS and VI-GPS results. From the ship handling maneuverability indices T and K, DRP had different results of the maneuverability indices with K-GPS and VI-GPS. During leaving and entering the port, VI-GPS showed different trails compared with the results by K-GPS and DRP due to the integral error not for the velocity information of VI-GPS. From these experimental results, VI-GPS is assessed as bellow:

- There is no time delay from speed measurement.
- The position error increases according to the time proceeding due to the integral error.
- Speed information is obtained with quite good accuracy or more compared to K-GPS.

For the future study, because of the integral error of VI-GPS according to time proceeding, it is necessary to improve the integral error with more accurate corrections.

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