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Experimental Results of Ship-To-Ship Lightering Operations Applied Velocity Information GPS

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Abstract : *A ship-to-ship (STS) lightering operation takes place in order to transfer cargo (e.g. crude oil or petroleum products) between an ocean-going ship and a service ship alongside it. Instrumental measurements to accurately determine the relative speeds and distances during the approach between the vessels would benefit the operational safety and efficiency. A velocity information GPS (VI-GPS) system, which uses the instantaneous velocity measures from carrier-phase Doppler measurement, has been applied in a field observation onboard a service ship (Aframax tanker) approaching a ship-to-be-lightered (VLCC) in open waters. This article proposes to apply VI-GPS as the input sensor to a guidance and decision-support system aiming to provide accurate velocity information to the officer in charge of an STS operation. A method for precise velocity measurement using VI-GPS was described and the measurement results were compared each other with the results of Voyage Data Recorder (VDR) and VI-GPS that showed the concept of a guidance and decision-support system applying VI-GPS with the field test results during STS operations. Also, it turned out that VI-GPS has sufficient accuracy to serve as an input sensor from the field test results.*

Key words : *ship-to-ship lightering, ship-to-be-lightered, service ship, kinematic GPS, carrier-phase-derived Doppler measurement, velocity information GPS, Voyage Data Recorder*

1. Introduction

A ship-to-ship (STS) transfer is an operation where cargo is transferred between an ocean-going ship and a service ship alongside each other in open waters. A typical operational pattern is where two vessels, a service ship (SS) and a ship-to-be-lightered (STBL), are underway with speeds in the range of 4 ~ 6 knots in Figure 1 (ICS & OCIMF, 2005). The initial approach phase is an intentional maneuver by the service ship whose aim is to obtain the required safety distance of about 150 m between SS and STBL, while the final approach is maneuvering towards the STBL and operating alongside until the ships have been moored together for cargo transfer. Another type of STS lightering is where the service ship approaches an anchored STBL.

All STS operations are inherently different because of variations in environmental conditions and differences in maneuvering characteristics of the ships involved. The final approach phase is particularly critical in order to avoid steel-to-steel contact. The mooring master in charge of an STS lightering currently has no relevant equipment at his disposal in determining relative speeds and distances with sufficient accuracy in the final stage; maneuvering orders are mainly based on visual observations (Pedersen, 2008).

The kinematic GPS is well known for providing accurate positioning in the cm range, but it requires the reference station to be within 20 km of the receiver. For that reason, velocity information GPS (VI-GPS) (Hou, 2005), which has shown sufficient accuracy in comparisons to kinematic GPS with DOP < 4.8, has been applied to determine relative speeds and distances for STS lightering (Yoo, 2009). The velocity is estimated using the carrier-phase-derived Doppler that is a measure of mean velocity between observation epochs, and one of the main advantages of VI-GPS is that user positioning can be determined using a stand-alone GPS receiver (Luise, 2004).

A STS field test was carried out in the US Gulf of Mexico and the results from a field test involved the observation of two tankers, an Aframax (SS) and a VLCC (STBL). The STBL maintained a constant course and speed while the service ship approached from a starboard side of STBL in accordance with the pattern of an STS operation.

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VI-GPS was applied in the test and the experimental results were compared with data logged from the Voyage Data Recorder (VDR). A simple concept for a guidance and decision-support system for STS operations using VI-GPS as an input sensor is presented.

Fig. 1 Two tankers coming alongside in open waters to commence cargo transfer (The forward speed during the approach is in the range of 4-6 knots according to A courtesy of SPT Ltd.)

2. Velocity information GPS

The velocity of a movable body can be determined using Doppler measurements generated by the GPS receiver or the carrier-phase derived Doppler measurements as long as the satellite velocity is precisely known. Doppler measurements generated by the GPS receiver are measures of instantaneous velocity over a very short time interval, whereas measurements derived from the carrier-phase are measures of mean velocity between observation epochs. Velocity integration with respect to time is the displacement during the period between the two epochs.

A method for precise velocity measurement using velocity information GPS is described in this section. The carrier-phase rate can be approximated as follows (Hou, 2005) (Luise, 2004):

$$\Phi_k^j \approx \frac{\Phi_{k+\Delta t}^j - \Phi_{k-\Delta t}^j}{2\Delta t} \tag{1}$$

where Φ is carrier-phase observation, superscript j represents the satellite, and subscript k and Δt are the observation epoch and time interval of the observation, respectively.

The observation equation for GPS carrier-phase measurements at epoch k is as follows:

$$\Phi = \rho + c(dt - dT) + \lambda N - I + T + M + \varepsilon_\Phi \tag{2}$$

where Φ [m] is the carrier phase measurement of the receiver; ρ [m] is the distance between the satellite and the receiver; c [ms-1] is the speed of light in a vacuum; dt [s] is the bias of the receiver clock; dT [s] is the bias of the satellite clock; λ [m] is the carrier wavelength; N is the integer ambiguity of carrier phase; I [m] is the bias of the ionospheric delay; T [m] is the bias of the tropospheric delay; M [m] is the multipath delay; and ε_Φ [m] is the measurement noise and errors which cannot be modeled.

Time differential observations are obtained by subtracting the observations at the previous epoch k -1 from those at the present epoch k. If the interval of observations is short (<< 1 sec), it is assumed that variations of propagation errors in the ionosphere and troposphere are small and negligible. The time differential observation is expressed in Eq.(3) and temporal differences remove the phase ambiguities.

$$\delta\Phi = \delta\rho + c(\delta dt - \delta dT) + \varepsilon_\Phi \tag{3}$$

Here, the symbol δ is the time differential operator. The observation equation can be written as follows:

$$\boldsymbol{l} = f(\boldsymbol{X}) + \boldsymbol{V} \tag{4}$$

where $\boldsymbol{l}$ is the vector of observations:

$$\boldsymbol{l} = [\delta\Phi_1\, \delta\Phi_2 \cdots \delta\Phi_N]^T$$

and $f(*)$ is the vector of known functions mapping $\boldsymbol{X}$ to $\boldsymbol{l}$ with $\boldsymbol{X}$ as the vector of unknown parameters on the form:

$$\boldsymbol{X} = [(\delta\rho_1 + c(\delta dt_1 - \delta dT_1)) \cdots (\delta\rho_N + c(\delta dt_N - \delta dT_N))]^T$$

$\boldsymbol{V}$ is the vector of residuals; subscript N is the satellite number; and T is the vector transposition.

The equations must be linearized with respect to the unknowns before performing a least squares adjustment. Linearization of Eq.(4) is made by replacing the non-linear functions with their Taylor series approximations expanded about an initial value of the solution vector $\boldsymbol{X}^0$, and by taking the first order terms only (Kaplan, 2006):

$$\boldsymbol{l} - f(\boldsymbol{X}^0) = \partial f / \partial \boldsymbol{X} \cdot d\boldsymbol{X} + \boldsymbol{V} \tag{5}$$

or

$$\boldsymbol{W} = \boldsymbol{A}\boldsymbol{X} + \boldsymbol{V} \tag{6}$$

where $\boldsymbol{W}$ is the mis-closure vector; $\boldsymbol{l} - f(\boldsymbol{X}^0)$; $\boldsymbol{A}$ is the design matrix of partial derivatives evaluated by using $\boldsymbol{X}^0$; $\boldsymbol{X}$ is the vector of corrections to $\boldsymbol{X}^0$; and $\boldsymbol{V}$ is the residuals.

Assuming that the matrix $\boldsymbol{A}$ at the present epoch k is identical to the one at the previous epoch k-1, the least-squares solution of Eq.(7) is the displacement between the two epochs. The mis-closure vector $\delta\boldsymbol{W}$ obtained from Eq.(3) is distinguished from the observation equation for positioning obtained from Eq.(2):

$$\delta\boldsymbol{W} = \boldsymbol{A} \cdot \delta\boldsymbol{X} + \boldsymbol{V} \tag{7}$$

When the weight of measurement is not equal, the equation must be weighted with an observation weight matrix $\boldsymbol{P}$. When the double difference observation is used, the mathematical correlation has to be taken into account using the matrix $\boldsymbol{P}$. The normal matrix $\boldsymbol{N}$, the vector $\boldsymbol{U}$ and the least-squares solution are derived from the application of the least-squares principle ($\hat{\boldsymbol{V}}^T \boldsymbol{P} \hat{\boldsymbol{V}} \to$min.) to Eq.(7) as follows:

$$\boldsymbol{N} = \boldsymbol{A}^T \boldsymbol{P} \boldsymbol{A} \tag{8}$$

$$\boldsymbol{U} = \boldsymbol{A}^T \boldsymbol{P} \delta\boldsymbol{W} \tag{9}$$

$$\delta\hat{\boldsymbol{X}} = \boldsymbol{N}^{-1} \boldsymbol{U} \tag{10}$$

Observations at a 1 sec interval give a solution for unit displacement, i.e. velocity. By using the position from absolute positioning with a single GPS receiver as the a priori position, the least-square solution provides the correction to the a priori position.

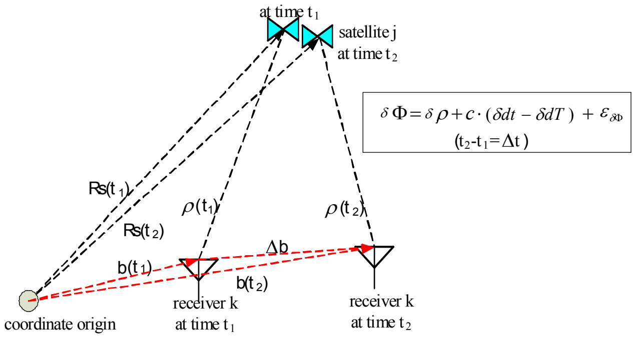


Fig. 2 Time differential carrier-phase measurement by VI-GPS

3. Experiment

3.1 Field test of STS operation

An STS lightering operation was conducted in the Galveston lightering zone of the US Gulf of Mexico in November 2009 between the VLCC Apollonia (STBL) and the Aframax tanker SPT Challenger (SS) shown in Fig.3. The general specifications of two ships are listed in Table 1. SPT Challenger that is an Aframax tanker served as SS is employed to install several antennas such as VI-GPS, AIS for the comparison of measurement performance. The antennas of VI-GPS, DGPS and AIS were all installed on the port bridge wing of the SPT Challenger from which data were logged during the approach and separation stages shown in Fig.4, and the VI-GPS data were compared with the VDR result. The weather condition was light wind and calm sea that has the mean wind speed under 3.2 knots. Movements of the STBL and relative distances were logged from the VDR with 1 Hz sampling frequency. VI-GPS data was logged with 5 Hz sampling frequency.

Fig. 3 SPT Challenger-SS (top) and Apollonia-STBL (bottom)

Table 1 SPT Challenter (SS) and Apollonia (STBL) general specifications, experimental conditions and data sampling details

	SPT Challenger (SS)	Apollonia (STBL)
Type	Aframax tanker	VLCC
DWT	150,000 [ton]	308,000 [ton]
LOA	240.5 [m]	333.3 [m]
Breadth	42 [m]	58 [m]
Service speed	11.4 [knot]	15.9 [knot]
Mean wind-direction	144 [deg]	
Mean wind speed	3.2 [knot]	
Sea state	Calm (rippled)	
Data length	1,542 [sec]	
Sampling-freqyencies	1 [Hz] (VDR) 5 [Hz] (VI-GPS)	

Fig. 4 Final stage of STS lightering between STBL and SS (top), GPS antennas (bottom left) and AIS wireless antenna (bottom right) installed on the wing bridge of the SS carried out in Gulf of Mexico

3.2 Experimental results

The voyage data logged by VDR and VI-GPS during the STS operation was analyzed. Fig.5 shows ship trails of SS and STBL, comparisons of SOG, surge speed and sway speed of the STBL by VDR (speed by Doppler log, heading by Gyro). The STBL's SOG and surge speed correspond well, but the resolution is poor because of rough sampling. Sway speed changed within ± 1 knot, and it became stable as the tankers came closer in the last 10 minutes interval.

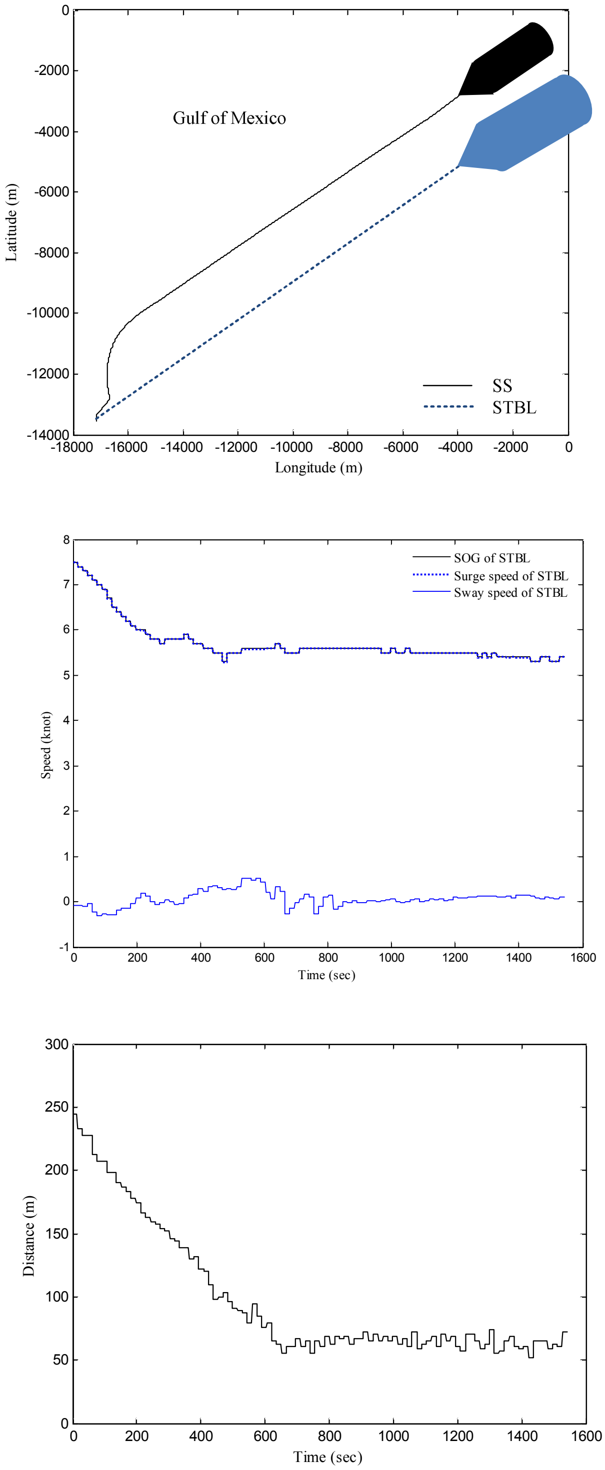


Fig. 5 Ship trails (top), SOG, surge and sway speeds of the STBL (mid) and relative distances(bottom) during STS lightering final stage from data in radar images as provided by VDR

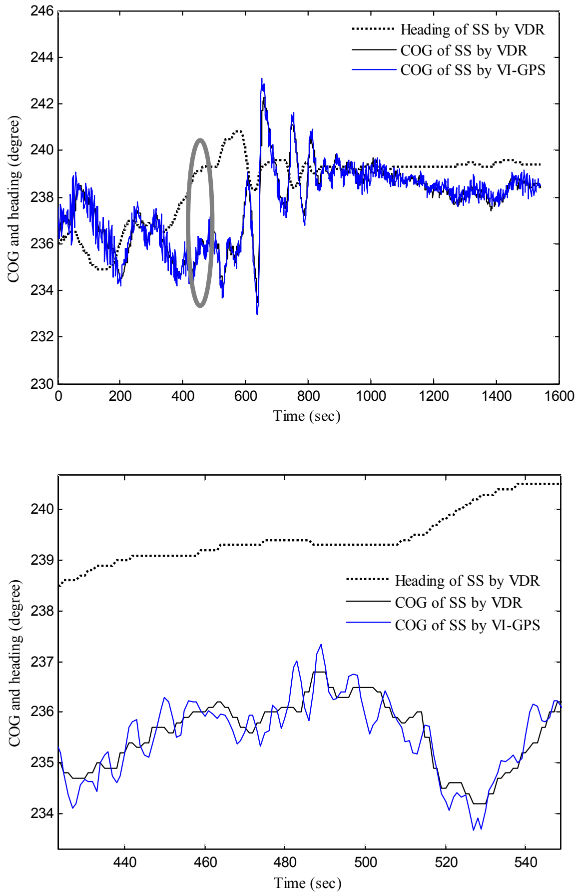


Fig. 6 SS heading and COG as provided by VDR and VI-GPS (top-all, bottom-magnified)

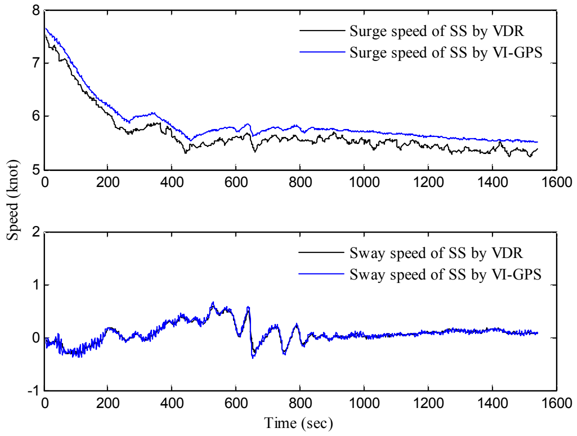


Fig. 7 SS surge (top) and sway (bottoms) speeds by VDR and VI-GPS

Fig. 6 shows SS heading (black dotted) by VDR, SS COG (black solid) by VDR and VI-GPS (blue solid). Results highlighted by the grey circle are magnified and it clearly shows that VI-GPS is more sensitive to wave movements in terms of COG results. Fig.7 shows SS surge speeds by VDR (black solid) and by VI-GPS (blue solid). VI-GPS results show consistently higher values than the VDR results and are more stable in surge speed result. Fig.8 shows the results for measurement random errors of surge and sway speeds by VDR (black solid) and VI-GPS (red solid). The result of surge speed by VDR shows larger random errors in comparison with VI-GPS while the trend is opposite for the sway speed. Table 2 shows the STD (standard deviation) values of random errors in surge and sway speeds of by VDR and VI-GPS, having eliminated moving average as shown in Fig.8. It is shown that VI-GPS is more sensitive to the subtle motion of the ship movements or wave effects.

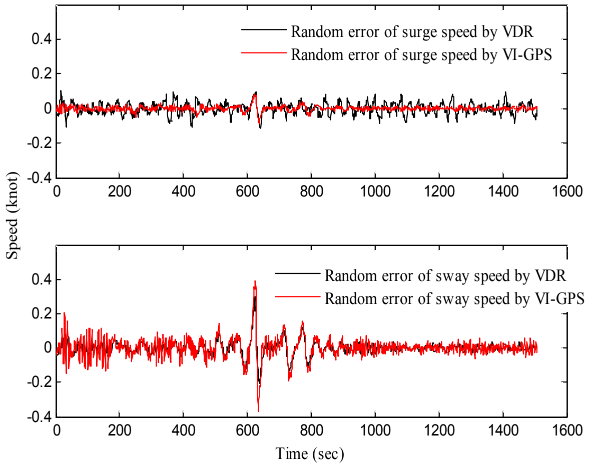
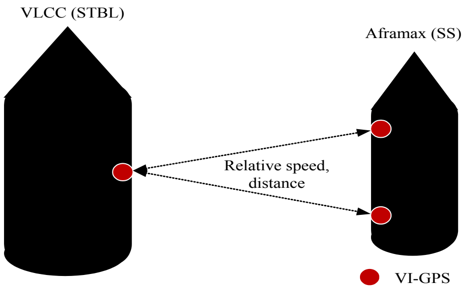


Fig. 8 Measurement random errors in surge (top) and sway (bottom) speeds by VDR and VI-GPS

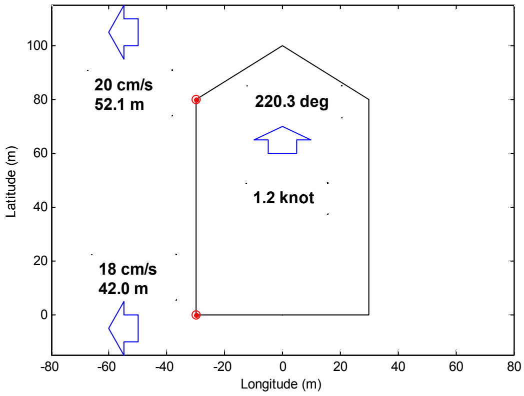
Table 2 STD (standard deviation) of measurement random errors in surge and sway speeds by VDR and VI-GPS

	Surge speed random error [cm/s]	Sway speed random error [cm/s]
VDR		
1-1508 [sec] (843-1508 [sec])	1.775 (1.726)	2.095 (0.800)
VI-GPS		
1-1508 [sec] (843-1508 [sec])	0.748 (0.408)	3.083 (1.227)

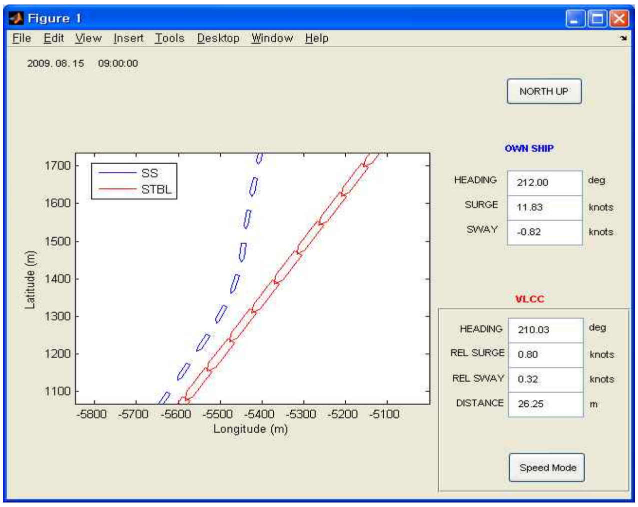
Fig.9 shows a simplified concept of a guidance and decision-support system applying VI-GPS to be used in STS operations. The configuration set-up is proposed with installation of one VI-GPS antenna on the STBL and two antennas on the service ship. A hand-held device can display the most essential information to the mooring master when standing on the bridge wing in the final approach phase while the main display can be installed on the bridge and include more navigation data.



(a) Installation configuration of VI-GPS during STS operation



(b) Display concept of a hand-held device that gives approaching speed in the final approach phase during STS operation



2009. 08. 15 09:00:00

OWN SHIP

HEADING 212.00 deg
SURGE 11.83 knots
SWAY -0.82 knots

VLCC

HEADING 210.03 deg
REL SURGE 0.80 knots
REL SWAY 0.32 knots
DISTANCE 26.25 m

(c) Display concept of a guidance and decision-support onboard system for STS operation

Fig. 9 Configuration set-up of VI-GPS between STBL and SS (a), display concept of a hand-held device (b), display outline of a guidance and decision-support system for STS operations (c)

4. Conclusion

A ship-to-ship (STS) lightering operation in open waters requires human operators with considerable expertise and experience as no relevant equipment for determining relative speeds and distances with sufficient accuracy are currently in use. Therefore, the development of a guidance and decision-support system called for, assisting ship navigation officers in successfully completing close-proximity navigation challenges, thus contributing to the operational safety and efficiency.

A field test, observing an Aframax tanker as service ship and a VLCC as ship-to-be-lightered, was also conducted. Navigation data were logged by Voyage Data Recorder (VDR) and compared with the results achieved by velocity information GPS (VI-GPS).

VI-GPS results for surge and sway speeds were presented and compared with the equivalent VDR results. This comparison showed that VI-GPS is more sensitive to ship and wave movements than VDR. The moving average of speeds by VI-GPS and VDR was eliminated to identify the random errors of each system, and the VDR results showed higher-value random errors in surge speed comparison. On the other hand, VI-GPS showed random errors of higher value than VDR in sway speed comparison.

A simple concept for a guidance and decision-support system for STS operations using VI-GPS was presented. VI-GPS is believed to be sufficiently accurate to serve as an input sensor, providing information about relative speeds and distances in a guidance and decision-support system for navigation officers to use during STS operations.

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