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INTEGRITY ANALYSIS OF REAL-TIME PPP TECHNIQUE WITH IGS-RTS SERVICE FOR MARITIME NAVIGATION

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ABSTRACT:

Open sea and inland waterways are the most widely used mode for transporting goods worldwide. It is the International Maritime Organization (IMO) that defines the requirements for position fixing equipment for a worldwide radio-navigation system, in terms of accuracy, integrity, continuity, availability and coverage for the various phases of navigation. Satellite positioning systems can contribute to meet these requirements, as well as optimize marine transportation. Marine navigation usually consists of three major phases identified as Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking with alert limit ranges from 25 m to 0.25 m. GPS positioning is widely used for many applications and is currently recognized by IMO for a future maritime navigation. With the advancement in autonomous GPS positioning techniques such as Precise Point Positioning (PPP) and with the advent of new real-time GNSS correction services such as IGS-Real-Time-Service (RTS), it is necessary to investigate the integrity of the PPP-based positioning technique along with IGS-RTS service in terms of availability and reliability for safe navigation in maritime application. This paper monitors the integrity of an autonomous real-time PPP-based GPS positioning system using the IGS real-time service (RTS) for maritime applications that require minimum availability of integrity of 99.8% to fulfil the IMO integrity standards. To examine the integrity of the real-time IGS-RTS PPP-based technique for maritime applications, kinematic data from a dual frequency GPS receiver is collected onboard a vessel and investigated with the real-time IGS-RTS PPP-based GPS positioning technique. It is shown that the availability of integrity of the real-time IGS-RTS PPP-based GPS solution is 100% for all navigation phases and therefore fulfil the IMO integrity standards (99.8% availability) immediately (after 1 second), after 2 minutes and after 42 minutes of convergence time for Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking, respectively. Moreover, the misleading information is about 2% for all navigation phases that is considered less safe is not in immediate danger because the horizontal position error is less than the navigation alert limits.
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1. INTRODUCTION

The maritime navigation accuracy requirements for radionavigation systems such as GPS are specified by the International Maritime Organization (IMO). Marine navigation usually consists of three major phases identified as Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking with alert limit requirement ranges from 25 m to 0.25 m. To navigate safely, the pilot needs highly accurate and reliable determination of position almost continuously together with information depicting any tendency for the vessel to deviate from its intended track. Standards or requirements for safety of navigation are developed around the above three navigation phases. The accuracy and integrity of position-fixing shall meet the minimum requirements for maritime users. Table 1 shows the IMO minimum maritime user requirements for horizontal absolute accuracy and integrity of GNSS based positioning (IMO, 2002; IMO, 2004; Parkins, 2009; El-Diasty, 2010).

Navigation phase	Horizontal absolute accuracy (m)	Integrity			Availability (per 30 days)
		Alert limit (m)	Time to alarm (s)	Integrity risk (per 3 hours)	
Ocean/Coastal/Port approach/Inland waterway	10	25	10	10^{-5}	99.8%
In port navigation	1	2.5	10	10^{-5}	99.8%
Automatic docking	0.1	0.25	10	10^{-5}	99.8%

Table 1. IMO minimum maritime user requirements accuracy and integrity of GNSS based positioning (IMO, 2002)

GPS positioning is widely used for many applications and is currently recognized by IMO for a future maritime navigation (IMO, 2002). Therefore, the GPS positioning techniques ranges from Real-time kinematic (RTK) techniques to Differential techniques (DGPS) along with GNSS augmentation systems and inertial navigation systems have been investigated by many researchers to investigate whether these techniques meets the IMO requirements form different maritime navigation phases (Parkins, 2009; El-Diasty, 2010; Moore et al., 2001; Fairbanks et al., 2004; Moore et al., 2008). Most recently, the International GNSS Service (IGS) produces precise GPS satellite orbit and clock corrections that are available in real-time. These products are known as the IGS Real-Time Service

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(IGS-RTS). Moreover, Precise Point Positioning (PPP) technology have shown promising light towards the development of an autonomous GPS solution for positioning applications where one GPS receiver is only employed. With the advancement in GPS positioning techniques such as PPP positioning and with the advent of new real-time GNSS correction services such as IGS-RTS service, it is necessary to assess the possibility of a wider role of the PPP-based positioning technique along with IGS-RTS service and their capability to enable new maritime applications. El-Diasty and Elsobeiey (2015) investigated the accuracy of PPP-based positioning technique along with IGS-RTS service for maritime navigation and concluded that the real-time IGS-RTS PPP-based GPS solution fulfils IMO requirements at 95 confidence level for maritime applications with an accuracy requirement range from 10 m for ocean/coastal/port approach/inland waterways navigation to 1.0 m for in port navigation but cannot fulfil the automatic docking application with an accuracy requirement of 0.10 m. This paper investigates the integrity of an autonomous real-time PPP-based GPS positioning system using the IGS real-time service (RTS) for maritime applications that require a reliable positioning system according the IMO integrity standards. To examine the integrity of the real-time IGS-RTS PPP-based technique for maritime applications, kinematic data from a dual frequency Trimble BD950 GPS receiver is collected onboard a vessel owned by the Canadian Hydrographic Service (CHS) and investigated with the real-time IGS-RTS PPP-based GPS positioning technique. The integrity of the real-time IGS-RTS PPP-based GPS solution is investigated when IMO integrity parameters requirements for ocean/coastal/port approach/inland waterways, in port navigation and the automatic docking application are considered.

2. REAL-TIME IGS-RTS PPP-BASED METHOD

Typically, real-time kinematic (RTK) RTK-based GPS method is widely used to provide positioning solution for maritime applications that requires an accurate positioning. However, RTK-based GPS method requires the existing of at least one reference receiver to provide regional correction information to the rover receiver. The major drawback of the RTK-based GPS method is the distance between the base station and the rover. Precise Point Positioning (PPP) has proven that it is a valuable method for single point positioning which can be applied over a global scale. By the presence of the IGS, the PPP accuracy can reach a few millimeters with daily observations (Yigit et al., 2013; Rizos et al., 2012; El-Mowafy, 2011). However, kinematic positioning using PPP, even using the final IGS products, needs about 30 min to obtain centimeter precision. Currently, the IGS provides an accurate GPS satellite orbit and clock corrections for real-time applications. These accurate real-time products are known as the IGS Real-Time Service (IGS-RTS). IGS-RTS utilizes the GPS data from more than 130 globally distributed stations to estimate the GPS satellite orbit and clock corrections. The IGS-RTS correction products are delivered to users over the Network Transport of RTCM by Internet Protocol (NTRIP) (IGS, 2015).

The objective in this paper is to estimate the real-time IGS-RTS PPP-based navigation solution and investigate whether this navigation solution can meet the international standards (IMO standards) for maritime navigation. In the real-time IGS-RTS PPP-based GPS method, the GPS dual frequency measurements are employed to generate the so-called ionospheric-free linear combination, which remove the ionospheric error. The observation equations for ionospheric-free pseudorange code and carrier phase measurements are processed to estimate the real-time IGS-RTS PPP-based GPS positions. To provide centimeter-level accuracy, after applying the major orbit, clock corrections and tropospheric dry corrections, the pseudorange and carrier phase measurement must be further corrected. This includes taking into account different corrections such as phase wind up effect, satellite antenna offset, solid earth tides, ocean loading, earth rotation parameters and eccentricity relativistic effect and Sagnac effect. Kouba and Heroux (2001), Leick (2004), Hofmann-Wellenhof et al. (2008), Laurichesse et al (2009) and Leandro (2009) are the main references for PPP-based and RTK-based GPS solutions. The PPP-based GPS solution requires precise satellite position and corresponding clock information. For post-processing applications, PPP-based GPS solution is obtained using IGS final and rapid products that provide the estimated satellite orbit and clock corrections. For real-time applications, PPP-based GPS solution can be obtained using an IGS Ultra-Rapid product with predicted satellite orbit and clock corrections or RTS service that provide instantaneous satellite orbit and clock corrections. Table 2 shows the accuracy of different IGS products and shows that RTS products and Ultra-Rapid products as well as the broadcast data can be used for real-time applications. It should be noted that, the accuracy of a satellite clock correction is fundamental to the final positioning solution using a PPP method. The root-mean-square of the current IGS-RTS satellite clock product is about 0.5 ns. Recent researches showed that using the IGS-RTS, a user with a single GPS receiver can obtain precise results comparable to the RTK technique (Grinter et al., 2013). However, it is necessary to assess the possibility of a wider role of the PPP-based positioning technique along with IGS-RTS service and their capability to enable new maritime applications.

Product	Parameter	Accuracy	Latency
Real-Time Service (RTS) (estimated)	orbit	5 cm	25 s
	clock	0.5 ns	
Ultra Rapid (predicted)	orbit	10 cm	real time
	clock	5 ns	
Ultra Rapid (estimated)	orbit	3 cm	3 hrs
	clock	0.2 ns	
Rapid (estimated)	orbit	2.5 cm	7 hrs
	clock	0.10 ns	
Final (estimated)	orbit	2 cm	14 days
	clock	< 0.10 ns	

Table 2. Precise GPS satellite orbits and clock corrections provided by the IGS (IGS, 2015)

In autonomous GPS processing, the GPS raw data collected from an autonomous GPS receiver can be processed with real-time satellite orbit and clock corrections using the IGS-Ultra-Rapid predicted products or the IGS-RTS instantaneous products by employing one of the many PPP software packages such as CSRS-PPP developed by Natural Resources Canada (NRCan), GPS Analysis and Positioning Software (GAPS) developed by Rodrigo Leandro (University of New Brunswick), Automatic Precise Positioning Service (APPS) developed by Jet Propulsion Laboratory (JPL), magicGNSS by GMV). The type of the developed PPP filter to compute the position is fundamental such as a simple weighted least square filter, a sequential least squares filter and a kalman filter. The applied filter determines the quality of the PPP software. Therefore, the above PPP software packages provide different solution. It should be noted that Martin et al. (2005) showed that the CSRS-PPP of NRCan and magicGNSS of GMV produce the most favorable and comparable results for kinematic positioning, therefore the CSRS-PPP software of NRCan was employed in developing the real-time IGS-RTS PPP-based GPS navigation solution investigated in this paper.

3. INTEGRITY ANALYSIS

Integrity is a measure of the trust which can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts) when the system must not be used for the intended operation. It is the International Maritime Organization (IMO) that defines the requirements for position fixing equipment for a worldwide radionavigation system, in terms of accuracy, integrity, continuity, availability and coverage for the various phases of navigation. Integrity is defined by the integrity risk, time to alert and alert limit requirements:

- Integrity risk: it is the probability of an undetected (latent) failure of the specified accuracy. It is expressed per hour or per operation. A positioning failure is defined to occur whenever the position solution error exceeds the applicable Horizontal Protection Level (HPL) or the Alert Limit (AL) (if the equipment is aware of the navigation mode).
- Time To Alert: it is the maximum allowable time interval between system performance ceasing to meet operational performance limits and the appropriate integrity monitoring subsystem providing an alert.
- Alert limits: for each phase of flight, to ensure that the position error is acceptable, alert limits are defined that represent the largest position error which results in a safe operation.

To investigate the integrity of the system over the time for an application, the system availability and the misleading information shall be estimated at the given integrity standards requirements of the intended application. Availability is the ability of the navigation system to provide the required function and performance at the initiation of the application under consideration and is expressed as a percentage of time. The availability determination relies on the estimation of the HPL and the assumption that reference positions are available that allow computing the actual Horizontal Position Error (HPE) over the time. HPL is an upper bound that the position error shall not exceed without being detected and is an important parameter that determines the availability of integrity. The HPL is computed at every epoch by the user, and provides an estimation of the boundary of the current position error. The HPL is estimated based on the least squares residual RAIM method. The HPL is computed referring to the worst satellite (Ryan et al., 1996; Walter and Enge, 1995):

$$HSLOPE_{max} = max_j\left(HSLOPE_j, j = 1, 2 \ldots .N_{sat}\right) \quad (1)$$

where $HSLOPE_{max}$ is a linear relationship between the position error and the test statistics for the large satellite range error, N_{sat} is the number of visible satellite with in the selected mask angle in the precise point positioning and j is the satellite measurement number under consideration. Two types of *HPL* calculation method are carried out and the maximum value of them is considered as the final *HPL*. The first method (*HPL1*) is based on the estimation of the minimum detectable bias and the maximum slope and the other method (*HPL2*) is derived from the position estimate uncertainty along with the maximum slope as follows (Ryan et al., 1996; Walter and Enge, 1995):

$$HPL1 = HSLOPE_{max} \cdot P_{bias} \quad (2)$$

$$HPL2 = HSLOPE_{max} \cdot T_h + k_h \cdot \sigma_h \quad (3)$$

$$HPL = max(HPL1, HPL2) \quad (4)$$

where P_{bias} is the probability of minimum detectable error (form the non-central chi-square density function), T_h is the threshold for the sum of the squared measurement residuals (from the central chi-square distribution table), k_h is a factor that reflects the probability of false alert (from the standard normal distribution table) and σ_h is the horizontal position uncertainty from the least square position solution.

The navigation system provides misleading information at specific time when the position error HPE is higher that estimated boundary limit HPL (HPE/HPL>1) and is consider as an indicator for the safety level that the navigation system can provide to the intended application. Consequently, if MI > 1 and HPE<AL then the system is less safe with no immediate danger but if MI >1 and HPE>AL then system is less safe with high level of immediate danger.

In this paper, Figure 1 is employed to compare the HPE with the HPL where each point corresponds to a computed position. The applicable Alert Limit (AL) is also displayed. The horizontal blue line represents HPL = AL, the vertical blue line represents HPE = AL. The red line corresponds to HPE = HPL. Thus, Figure 1 is thus divided into 4 areas which correspond to the following cases:

- A: corresponding points are above the red line, which means that MI = HPE/HPL <1: the system is safe for use, since the error estimate provided to the user was larger than the actual error. Since HPL < AL, the system is considered available.
- B: MI = HPE/HPL >1, which means that the system is providing Misleading Information (MI): the system is less safe than the user thinks it to be. However, since points in B correspond to HPE < AL, the user is not in immediate danger.
- C: as in B, MI = HPE/HPL >1. Moreover, points in C correspond to HPE > AL: these positions should not be used since they do not meet safety requirements, but they may not be detected (since HPL<HPE). Thus, the user is provided Hazardously Misleading Information: the system is less safe than the user thinks, which could lead to danger.
- D: as in A, MI = HPE/HPL <1. The information provided to the user is thus safe. However, the system is unavailable since HPL > AL.

Then, availability and MI > 1 are estimated for the application under consideration with its integrity standards where:

- Availability: it corresponds to the percentage of time during which HPL<AL
- MI > 1: it corresponds to the amount of time during which HPE>HPL, meaning that the system is providing misleading information.

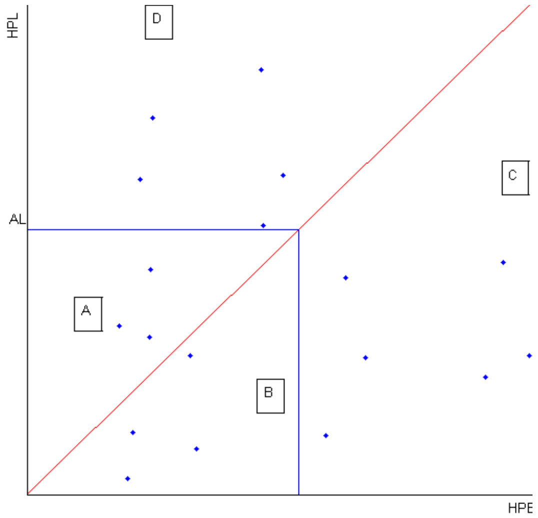

Figure 1. Integrity correlation (HPE and HPL correlation)

4. FIELD SYSTEM TEST

To examine the integrity of the investigated real-time GPS PPP-based methodology, dual frequency GPS data from a Trimble BD950 receiver was collected on July, 2015 in Lake of Ontario, onboard vessel owned by the Canadian Hydrographic Service (CHS) of the Department of Fisheries and Oceans (DFO). Figure 2 shows the test trajectory. The length of the collected kinematic data is 19800s (about 5.50 hours). The base station GPS measurements were simultaneously collected and employed to estimate the RTK-based GPS solution and considered as the reference solution to validate the real-time IGS-RTS PPP-based GPS position solution (our target).

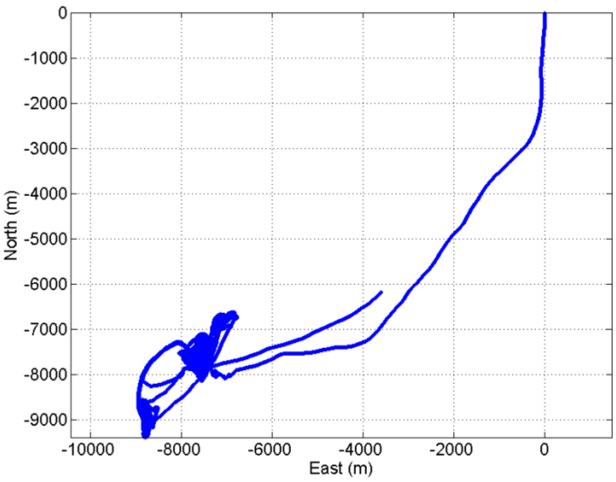

Figure 2. Test trajectory (blue line).

5. RESULTS AND DISCUSSION

The real-time PPP-based GPS positions were estimated from the CSRS-PPP software of NRCan with real-time satellite orbit and clock corrections using the IGS-RTS instantaneous products that is explained in section 2. Afterwards, the HPL was estimated using least square residual method that is explained in section 3 and the HPE was estimated as the horizontal position error differences of the the real-time IGS-RTS PPP-based GPS solution when compared against reference RTK-based GPS solution. Then, the correlation chart between the HPL and HPE along with the AL are employed to estimate the availability of the integrity and the misleading information of the real-time IGS-RTS PPP-based GPS technique with IGS-RTS instantaneous products. At the end, the availability of the integrity and misleading information are investigated whether it can meet the IMO integrity standards for safe and reliable maritime navigation. It is worth noting that the IMO minimum maritime user availability of the integrity requirement is 99.8% per 3 hours (see Table 1 in section 1).

Figure 3 shows the horizontal position error (HPE) that represented the difference (error) between the horizontal position estimated from the real-time IGS-RTS PPP-based GPS solution and the horizontal position estimated from RTK-based GPS position solution, where RTK is considered as a “reference” value. Figure 4 shows the HPL and the HPE along with the AL for Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking with alert limits 25 m, 2.5 m, and 0.25 m, respectively. It is shown that the performance of the real-time IGS-RTS PPP-based GPS solution converges to the favorable safe mode (HPL < AL) after 1 second, 125 seconds (about 2 minutes) and 2515 seconds (about 42 minutes) for Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking, respectively.

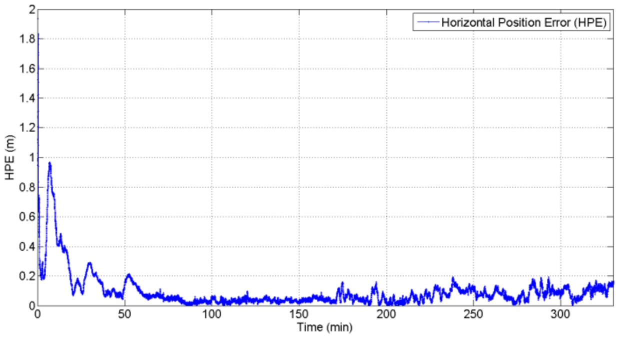

Figure 3. The HPE estimated from the difference between the real-time IGS-RTS PPP-based GPS solution and RTK-based GPS solution.

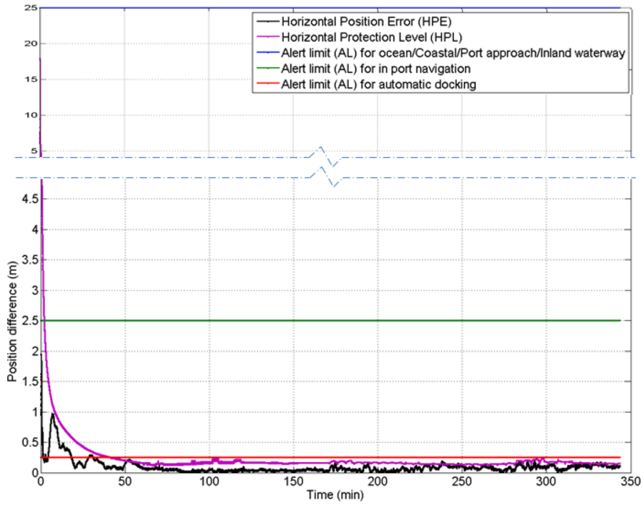

Figure 4. HPE against HPL along with AL from IMO standards.

Figures 5 through 7 show correlation between HPE and HPL after the convergence of the real-time IGS-RTS PPP-based GPS solution to the favourable performance for the Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking that illustrated in section 3. It is shown that the availability of integrity (area A + area B) of the real-time IGS-RTS PPP-based GPS solution is 100% for all navigation phases and therefore fulfil the IMO integrity standards for Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking (99.8%). Also, the misleading information (MI) is about 1.74%, 1.75% and 1.98% for Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking, respectively. However, it should be noted that the real-time IGS-RTS PPP-based GPS solution fulfils the IMO accuracy of for Ocean/Coastal/Port approach/Inland waterway and in port navigation applications with accuracy requirement ranges from 10m to 1m but cannot fulfil the automatic docking application with an accuracy requirement of 0.10m as concluded by El-Diasty and Elsobeiey (2015).

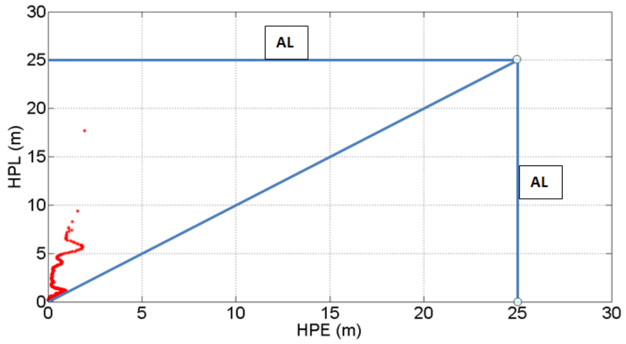

Figure 5. HPE and HPL correlation for Ocean/Coastal/Port approach/Inland waterway phase (after the convergence of the real-time IGS-RTS PPP-based GPS solution to the favorable performance – after 1 second).

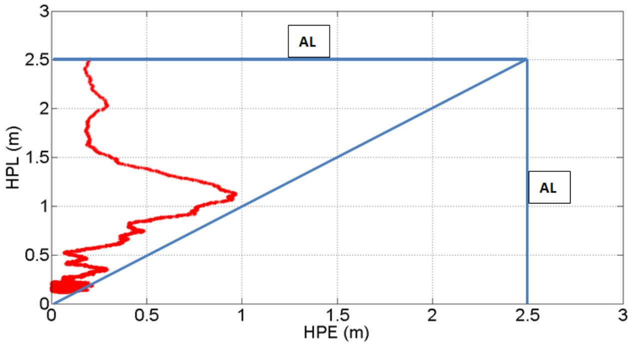

Figure 6. HPE and HPL correlation for in port navigation phase (after the convergence of the real-time IGS-RTS PPP-based GPS solution to the favorable performance – after 125 seconds).

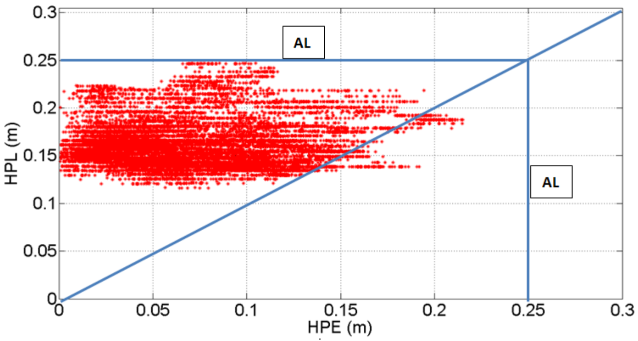

Figure 7. HPE and HPL correlation for in automatic docking phase (after the convergence of the real-time IGS-RTS PPP-based GPS solution to the favorable performance – after 2515 seconds).

6. CONCLUSION

This paper investigated an accurate autonomous worldwide real-time PPP-based GPS positioning system using the IGS real-time service (RTS) product with instantaneous precise satellite orbit and clock corrections for maritime applications that require an accurate positioning system and whether the achieved availability of integrity can meet the IMO integrity standards (99.8%).

To examine the performance of the investigated real-time IGS-RTS PPP-based technique for maritime applications, kinematic data from a dual frequency GPS receiver is collected onboard a vessel and investigated with the real-time IGS-RTS PPP-based GPS positioning technique. It is shown that the availability of integrity of the real-time IGS-RTS PPP-based GPS solution is 100% for all navigation phases and therefore fulfil the IMO integrity standards (99.8% availability) immediately (after 1 second), after 2 minutes and after 42 minutes of convergence time for Ocean/Coastal/Port approach/Inland waterway, in port navigation and automatic docking, respectively. Moreover, the misleading information is about 2% for all navigation phases that is considered less safe is not in immediate danger because the horizontal position error is less than the navigation alert limits.

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