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Potential Accuracy of GNSS PPP- and PPK-derived Heights for Ellipsoidally Referenced Hydrographic Surveys: Experimental Assessment and Results

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ABSTRACT

Ellipsodially referenced survey (ERS) is considered as one of the challenging issues in the hydrographic surveys due to the fact that the bathymetric data collected by this technique can be readily transformed either to the geodetic or the chart datum by application of some geoscientific models. Global Navigation Satellite Systems (GNSS) is a preferred technique to determine the ellipsoidal height of a vessel reference point (RP) because it provides cost-effective and unprecedentedly accurate positioning solutions. Especially, the GNSS-derived heights include heave and dynamic draft of a vessel, so as for the reduced bathymetric solutions to be potentially free from these corrections. Although over the last few decades, differential GNSS (DGNSS) has been widely adopted in the bathymetric surveys, it only provides limited accuracy of the vertical component. This technical barrier can be effectively overcome by adopting the so-called GNSS carrier phase (CPH) based techniques, enhancing accuracy of the height solution up to few centimeters. From the positioning algorithm standpoint, the CPH-based techniques are categorized under absolute and relative positioning in post-processing mode; the former is precise point positioning (PPP) correcting errors by the global or regional models, the latter is post-processed kinematic positioning (PPK) that uses the differencing technique to common error sources between two receivers. This study has focused on assessment of achievable accuracy of the ellipsoidal heights obtained from these CPH-based techniques with a view to their applications to hydrographic surveys where project area is, especially, few tens to hundreds kilometers away from the shore. Some field trials have been designed and performed so as to collect GNSS observables on static and kinematic mode. In this paper, details of these tests and processed results are presented and discussed.

Keywords: GNSS-PPP, GNSS-PPK, ERS, ellipsoidal height, potential accuracy

1. INTRODUCTION

surveys deal with the configuration of the bottom and adjacent land areas of oceans, lake, rivers, harbours, and other water forms of Earth (IHO 2005). To this end, they are periodically carried out to acquire georeferenced spatial data related to shoreline configuration, depths in the area of interest, and sea bottom composition. Note that the vertical datum is a one-dimensional coordinate system which defines the metric distance of a point from reference surface along a well-defined path (Bomford 1971). It is categorised accordingly to the type of the surfaces the height is referenced, such as tidal, geoid and ellipsoidal

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Table 1. Minimum standards for hydrographic surveys (IHO 2008).

Order	Special	1a	1b	2
Total horizontal uncertainty (95%)	2 m	5 m + 5% of depth	5 m + 5% of depth	20 m + 10% of depth
Total vertical uncertainty (95%)	a = 0.25 m b = 0.0075 m	a = 0.5 m b = 0.013 m	a = 0.5 m b = 0.013 m	a = 1.0 m b = 0.023 m
Range of TVU (95%)	0.25 ~ 0.35 m (depth: 1 ~ 40 m)	0.5 ~ 1.39 m (depth: 1 ~ 100 m)	0.5 ~ 1.39 m (depth: 1 ~ 100 m)	2.51 ~ 4.71 m (depth: 100 ~ 200 m)

surface. The hydrographic surveys have traditionally been conducted with reference to the tidal based chart datum (CD), whereas that of the topography acquires relative to the geoid (i.e. the geodetic datum realised by the mean sea level). Nevertheless, integration of the bathymetric and the topographic data has recently become indispensable for comprehensive spatial information analysis, including management of a coastal zone along the shoreline where covers the land and sea (Mill & Dodd 2014). In the hydrographic surveys, there has been, furthermore, a demand to overcome the technical challenge in the traditional approach that establishes the relationship between the instantaneous water level (IWS) and CD (ibid.). This is due to the fact that an uncertainty in the relationship between IWS and CD is one of major error sources affecting the reduced water depth. To this end, ellipsoidally referenced survey (ERS) has become one of the critical issues in the hydrography (Dodd et al. 2009, Rice & Riley 2011, Ligteringen et al. 2014, Mill & Dodd 2014); hence the bathymetric measurements collected to the reference ellipsoid enables to be transferred either to the CD or the geodetic datum by applying a series of geoscientific models, such as geoid, sea surface topography and hydro-dynamics model.

Differential Global Navigation Satellite Systems (DGNSS) technique, a pseudo range-based relative positioning scheme, has been mostly adopted for the hydrographic surveys due to the fact that it offers modest positioning accuracy (or uncertainty) especially for the horizontal component, as summarised in Table 1. Note that in the traditional approach, only the horizontal coordinates (i.e. latitude and longitude) are taken for the bathymetric modelling, whereas the vertical reference is given by the relation between IWS and CD. In the ERS for hydrography, the DGNSS does not always fulfil the required accuracy of the vertical component (Ligteringen et al. 2014). This is because the reduced water depth should sometimes be as accurate as few tens of centimetre with 95% confidence level, namely total vertical uncertainty (TVU) in Table 1. Since the TUV from the GNSS-based ERS reflects not only the observational errors of GNSS and echo-sounder but also the measurement translation and correction to the vertical line, it is suggested to determine the ellipsoidal heights with a minimum uncertainty. Mill & Dodd (2014) recommended for the hydrographic ERS to utilise the GNSS carrier phase (CPH)-based techniques: (a) real-time kinematic (RTK); (b) post-processed kinematic (PPK); (c) real-time GIPSY (RTG); and (d) post-processed precise point positioning (PPP). Note that RTK and PPK are the relative positioning algorithm, requiring setup of a reference station, whereas PPG and PPP use the absolute concept (Weston & Schwieger 2010, Leick et al. 2015). According to Dodd et al. (2009), these four techniques provide somewhat comparable accuracy for development of the water level buoy datum by GNSS.

Korean Hydrographic and Oceanographic Administration is currently preparing to introduce the ERS concept to its bathymetric surveys; hence development of a best practice for the GNSS vertical positioning is a prerequisite. In order to gain understanding of CPH- based techniques which is relatively new to the local hydrographic society, and evaluate potential accuracy of their ellipsoidal height estimation, field experiments were designed and performed to collect satellite observables in both static and kinematic modes. The measurements were processed in PPK and PPP modes using two common GNSS post-processing software: (a) RTKLIB Version 2.4.2, the open source program package for GNSS positioning; and (b) GrafNav Version 8.7, the commercial GNSS post-processing software provided by Novatel Waypoint. Medium-range GNSS relative positioning scheme was applied for PPK processing with a consideration of the ERS, where project area is few hundreds kilometres away from the land. In this paper, GNSS experiments as well as the processing and analysis methods are given, and this is followed by some discussion on achievable accuracy of the height determination by using the abovementioned software.

2. ELLIPSODIALLY REFERENCED HYDROGRAPHY SURVEYING

The IWS has been traditionally adopted as a surveying reference surface of water depth soundings in the hydrographic

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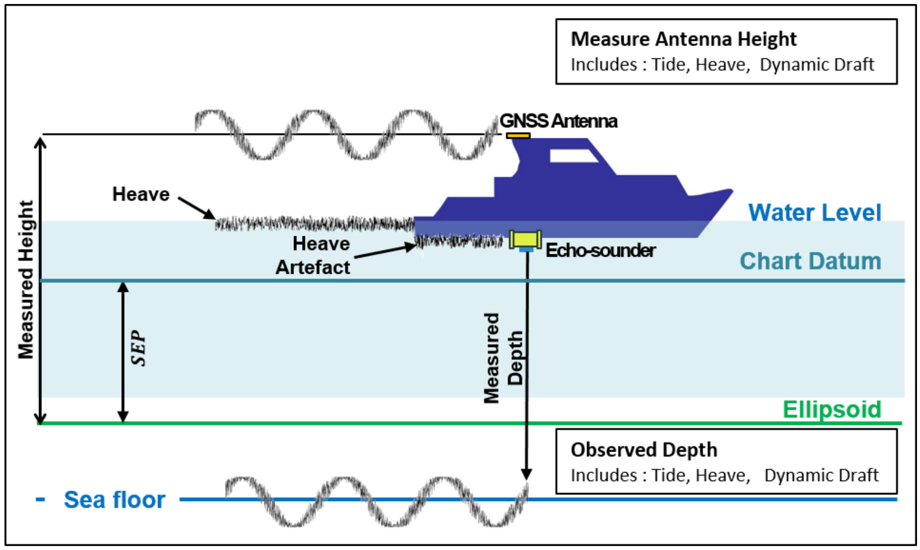

Fig. 1. Vertical positioning of ERS for hydrography (Mill & Dodd 2014).

surveys. As shown in Fig. 1, vertical movement of a vessel induced by tide, heave and dynamic draft should be appropriately corrected to the measured depth in order to transform it to the chart datum. Note that accuracy of the reduced water depth is decreased by uncertainties of these corrections. In addition, the bathymetric data by this traditional approach cannot be related to that of the topography due to absence of a common reference unless their offset is accurately modeled.

A drawback of the legacy hydrographic surveys can be overcome by adopting the ERS concept with help of GNSS positioning techniques that readily and accurately determine the ellipsoidal heights by reducing the CPH measurements. As presented in Fig. 1, all the vertical movements of the vessel are included in the GNSS antenna heights, so as not to be necessary for application of these corrections. Hence, the depth with the reference to the ellipsoid can be effectively derived with modest accuracy by application of the offset between the antenna and the echo-sounder and the pitch and roll reduction. It is of importance to take note that the ellipsoidal height of floor must be transformed to the CD by using the so-called separation model, see Dodd & Mills 2012 in more details. Over the last decade, the national geodetic agencies around the world have made their tremendous effort to develop precise geoid modes that mathematically describe the relationship between the two datum surfaces (i.e., the geoid and the ellipsoid), for instance the KNGeoid14 model in Korea (Lee & Kwon 2015). Using such a model, any of the bathymetric data with the reference to the ellipsoid can be related to the geodetic datum.

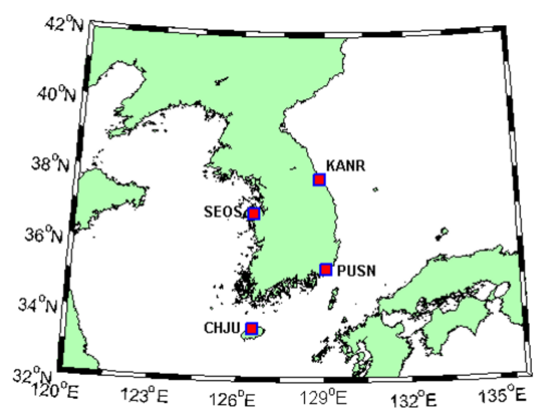

Fig. 2. CORS stations used in the static test.

3. MEASUREMENT AND METHODOLOGY

3.1 GNSS Measurement

In order to evaluate potential accuracy of the GNSS-derived ellipsoidal height using the PPP and PPK techniques, some tests on static and kinematic modes were carried out. For the static test, GNSS observables over 24 hours at 1 Hz sampling rate were obtained from the continuously operating reference stations (CORS) under operation by national geographical information institute of Korea (NGII). These stations are equipped with the state-of-art GNSS receivers (e.g. Trimble NetR9). As shown in Fig. 2, CORS stations close to shoreline were selected. Considering the PPK positioning, baseline between the stations are approximately 300 km. The NGII published coordinates of the stations are considered as the reference values for

Fig. 3. Setup of a kinematic test using a turntable.

potential accuracy evaluation in the tests. Note that the CORSs were used as the reference stations for both the static and kinematic tests in PPK mode.

3.2 GNSS Kinematic Test Configurations

A kinematic test was carried out by using a turntable as shown in Fig. 3. This setup provides the constrained circular trajectory and a constant ellipsoidal height. SK-702 antenna connected to SOKKIA GRS 2600 receiver was installed at the edge of the turning arm, collecting dual-frequency GPS observables for a total of 75 minutes at 1 Hz sampling rate with inclusion of 10 minutes static session. During the test, the number of visible GPS satellites ranged from eight to ten. In addition, a SOKKIA GRS 27000 receiver was setup approximately 100 meters away from the turntable in order to generate a reference trajectory through the short-range PPK processing that readily provides centimetre level positioning accuracy (Leick et al. 2015).

A survey vessel trial was performed on the West Nakdong River in Busan, Republic of Korea, by using three all-in-one GNSS receivers (i.e. SOKKIA GRX 1), see Lee et al. (2016) in details. Even though the test site is on the river, it can be considered as a lake in which the water surface is almost level as it is located near the estuary dyke. Since variation of the antennas' heights is mainly induced by the vessel's dynamics, it provides excellent testing environment for accuracy assessment of the GNSS-derived heights. The receivers were installed on roof of the vessel, GNSS dual-frequency measurements were logged at 1 Hz sampling rate for approximately two hours.

3.3 Methodology

As presented in Fig. 4, the GNSS observables were processed to estimate antennas' ellipsoidal height by using two types of GNSS software packages: (a) RTKLIB Version 2.4.2 (hereafter SW-1), an open source program package for GNSS positioning; (b) Waypoint GrafNav Version 8.7 (hereafter SW-2), a commercial post-processing software. Some features of these software are summarised in Fig. 4. Although GNSS (e.g. GPS, GLONASS and Galileo) measurements were obtained from the trials, only those of GPS were processed in this study.

It well known that the short-range PPK delivers centimetre-level positioning accuracy if carrier phase integer ambiguities are correctly resolved (Rizos 1997); hence this technique can be effectively utilised in a hydrographic ERS near shoreline in the case that a reference station is setup within about 20 kilometres from the survey area. To this end, accuracy evaluation of the GNSS-derived height in this research has only focused on the shipborne hydrographic surveys which cannot employ the short-range PPK, such as the medium-range PPK and PPP techniques. Note that solutions of the short-range PPK were used as reference values for a comparison with kinematic testing results of the medium-range PPK and PPP.

To model the satellite orbits errors effectively, the precise ephemeris provided by Centre for European Orbit Determination (CODE) were employed in the medium-range PPK and PPK processing. In the PPP processing, the so-called ionosphere-free linear combination (L3) was used to minimise the ionospheric effects, whereas the residual troposphere was estimated together with 3-D coordinates as an addition unknown state. However, both software on the medium-range PPK processing deals with these errors via different methods; the SW-1 estimates them from the double-differenced (DD) measurements, whereas the SW-2 takes an additional process for the ionosphere and uses a PPP engine to observe the actual tropospheric delay at the reference station, More details on these methods can be found in the user manual, see e.g. Takasu (2013) and Waypoint (2016). The final solutions are derived through weighted combination of a forward filtering and a backward smoothing on the ground that this approach offers a reduction in antenna position uncertainty as compared with the forward only (Dodd et al. 2009). In addition, the integer ambiguity resolution (AR) procedure was not attempted to both of PPP and the medium-range PPK processing; therefore the so-called float solutions were obtained. This is due to the fact that the AR of these techniques is still a challenge to rapidly reliably solve the problem (Leick et al. 2015).

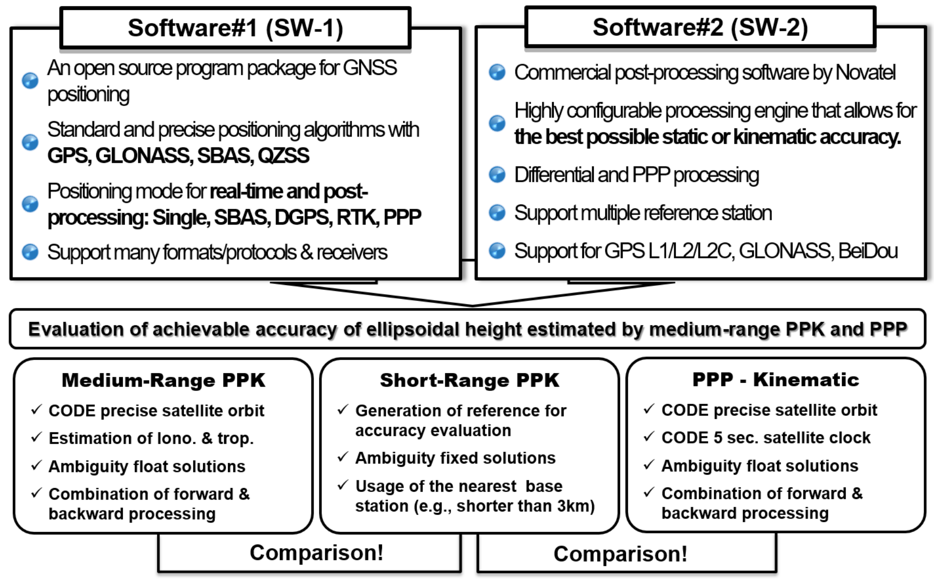

Fig. 4. GNSS data processing and result analysis methods.

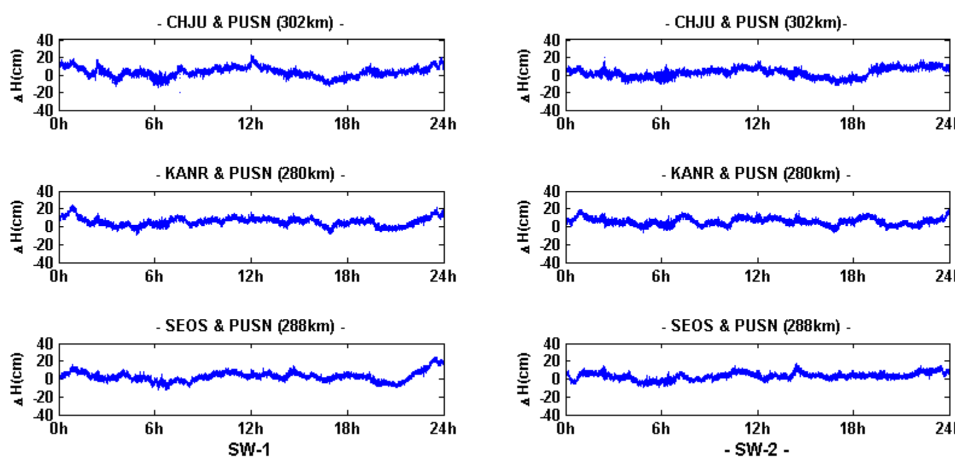

Fig. 5. Differences between the published and the GNSS medium-range PPK-derived heights of the static test: (a) SW-1 on the left; (b) SW-2 on the right.

For the sake of examining accuracy of the GNSS-derived ellipsoidal heights from the medium-range PPK and PPP solutions, their solutions were compared with the published coordinates for the static test as well as the short-range PPK solutions for the kinematic trials. Finally, root-mean-squares errors (RMSE) with 1-σ confidence level were computed for quantifying error of the estimated heights.

4. RESULTS AND DISCUSSION

4.1 Static Test

While time series of differences between the ellipsoidal heights published by the NGII and estimated by the medium-range PPK are presented in Fig. 5, those of the PPP are manifested in Fig. 6. In these figures, the graphs on left-hand side are results of the SW-1, whereas the SW-2 solutions are represented in the graphs on right-hand side. By and large, even though biases are not observed in these results for 24 hours, level of the differences slightly changes with respect to time, which would be caused by the residual troposphere. On the other hand, the results of the SW-1 depict that these differences gradually increase at the end of the time series, especially those of the medium-range PPK. It seems to be induced by smoother's initialisation of the backward processing. For instance, if the smoother overestimates the positional solutions during the initialisation, weighted combination of the two solutions becomes biased. Recall that the SW-1 uses the extended Kalman filter (i.e. EKF) to simultaneously estimate both the ionospheric and tropospheric effects, whereas the

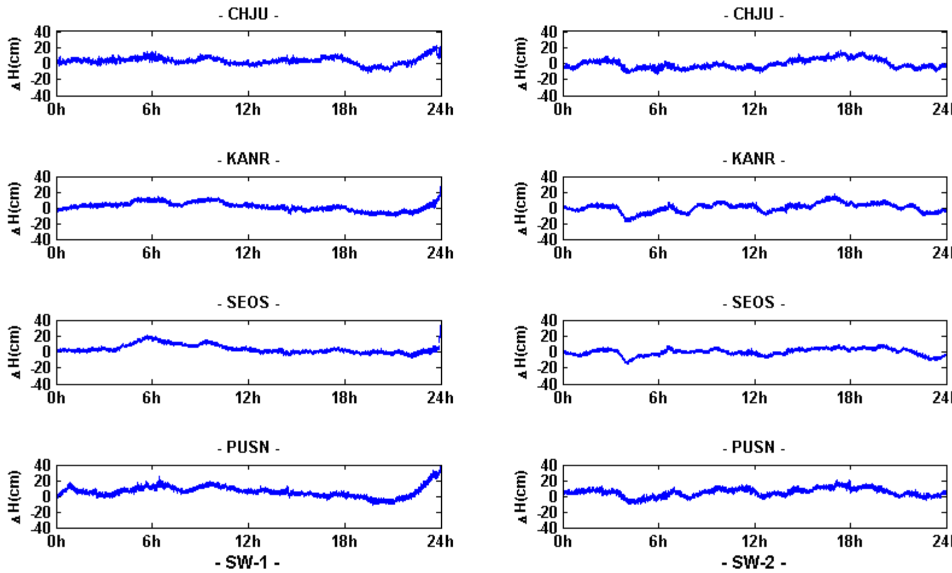

Fig. 6. Differences between the published and GNSS-derived heights of the static test by the PPP: (a) SW-1 on the left; (b) SW-2 on the right.

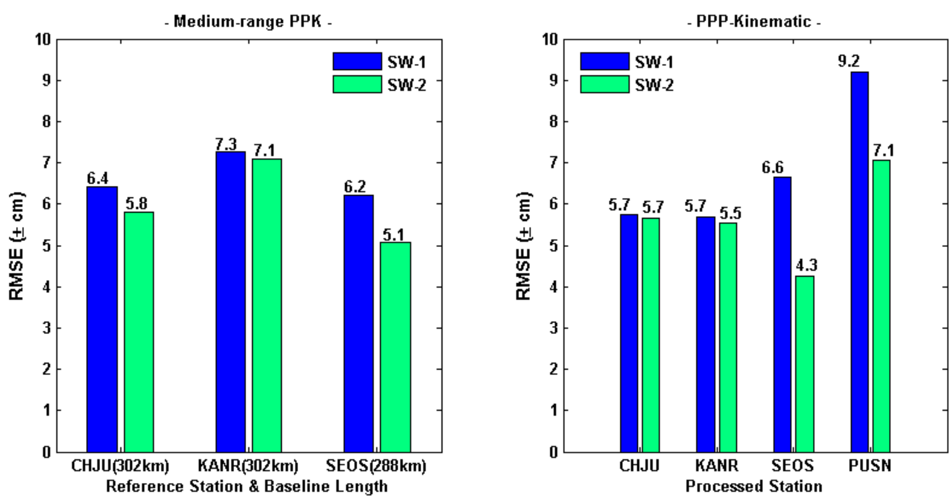

Fig. 7. RMSE of the GNSS-derived heights of the static test.

SW-2 performs the addition processing to handle these errors, which is a separate process from the GNSS antenna coordinate estimation.

Fig. 7 shows RMSE values of the GNNS-derived ellipsoidal heights of the static tests. Generally speaking, results of the SW-2 are slightly better than those of the SW-1, but the amount is limited. While the RMES of the medium-range PPK of the SW-1 ranges from ±6 to 7 cm, that of the SW-2 is around ±6 cm. On the other hand, it is of interest to observe that the SW-1's PPP solutions at SEOS and PUSN are relatively larger than the others, which would be attributed to the smoother's initialisation as previously mentioned.

Results of the static tests for 24 hours shown in Figs. 5 to 7 can be summarised as: (a) the SW-2 gives marginally better solutions in term of the accuracy; (b) the medium-range PPK and the PPP delivers comparable results in the height estimation, and the accuracy are better than ± 10 cm with 1-σ confidence level; (c) the accuracy of the PPP depends upon sight location, which would be correlated with the tropospheric condition.

4.2 Kinematic Trials

4.2.1 Turntable

For demonstration, horizontal trajectories obtained by the short- and medium-range PPK as well as PPP processing are presented in Fig. 8. Note that the medium-range PPK

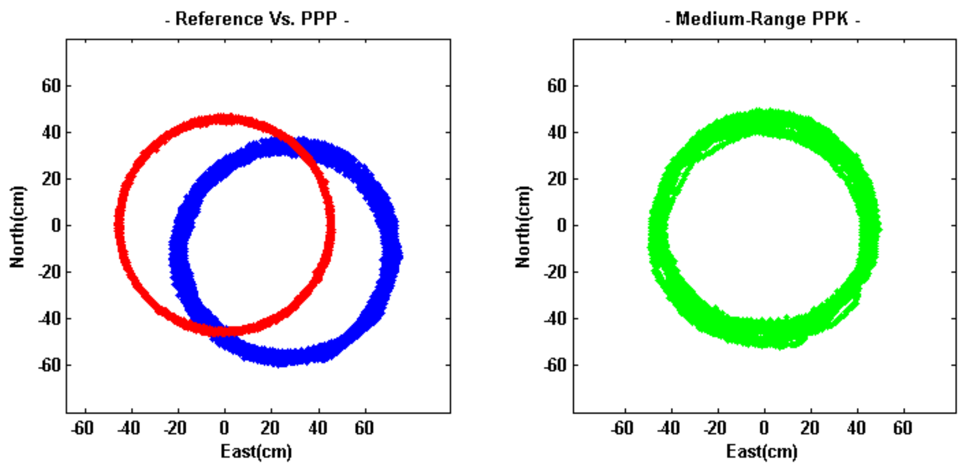

Fig. 8. Horizontal trajectories of the turn-table test: the left graph depicts comparison of the PPP (blue colored) with the reference (red colored), whereas the right graph presents that of the medium-range PPK.

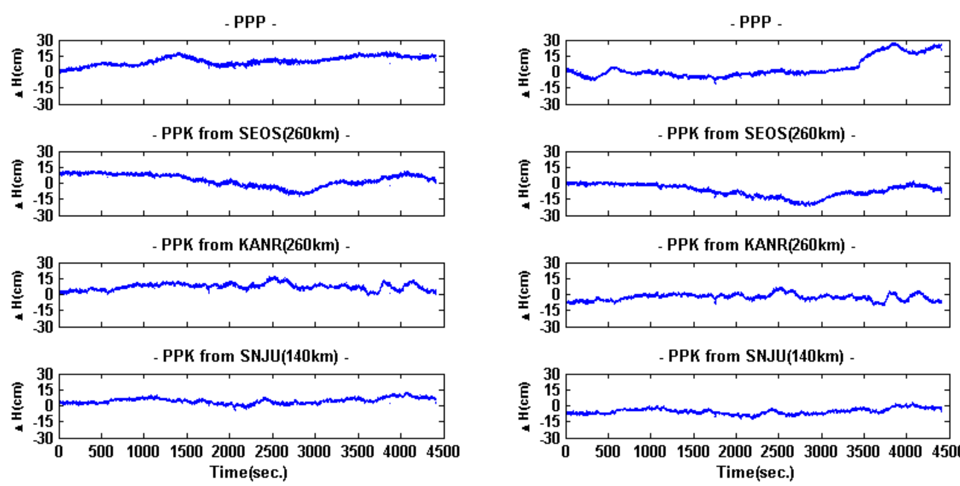

Fig. 9. Differences between the reference and the GNSS PPP-derived heights of the turntable test: (a) SW-1 on the left; (b) SW-2 on the right.

was derived with respect to the SEOS station of which baseline is approximately 260 km. As seen from the plots on the left, the red coloured line is the reference given by the short-range PPK, and the blue coloured line is the results of the PPK. On the other hand, the graph on the right shows the one estimated by the medium-range PPK. It is possible to appreciate precision of these solutions from thickness of these circles. The most critical point in these graphs to observe is the bias between the PPK and the PPP, which is probably caused by discrepancy of the geodetic datum adopted in each the solutions. Whilst the PPP solution is referenced to the global reference frame (e.g. IGS08), that of the PPK is aligned to the local geodetic datum, the so-called Korean geodetic datum 2002 (KGD 2002). Note that the crust of the Korean Peninsula' moves annually about 3.0 cm toward the southeast, but no significant vertical deformation is observed (Lee et al. 2010). Hence, if the PPP technique is used, a surveyor should be aware of the geodetic.

Fig. 9 shows time series of differences between the ellipsoidal heights of the short-range PPK (i.e. the reference values) and results of the PPP and the medium-range PPK: the graphs on the left are outcomes of the SW-1, and those graphs on the right are given by the SW-2. Note that for the turntable test, GNSS measurements were processed with respect to the three NGII CORS stations, forming baselines of which lengths range from about 140 to 260 km. Furthermore, RMSE values of all the solutions are given in a bar graph of Fig. 10. Comparing the RMSE of the PPK obtained by the two software, the SW-1 indicates relatively smaller values. Since the difference is ±1 cm from the single test, it is hard to interoperate which of the solutions provides better results in term of accuracy. On the other hand, looking into results of the medium-range PPK, the superiority of the software is not observed. It is also of interest to see the bar graph that the PPK's accuracy of the

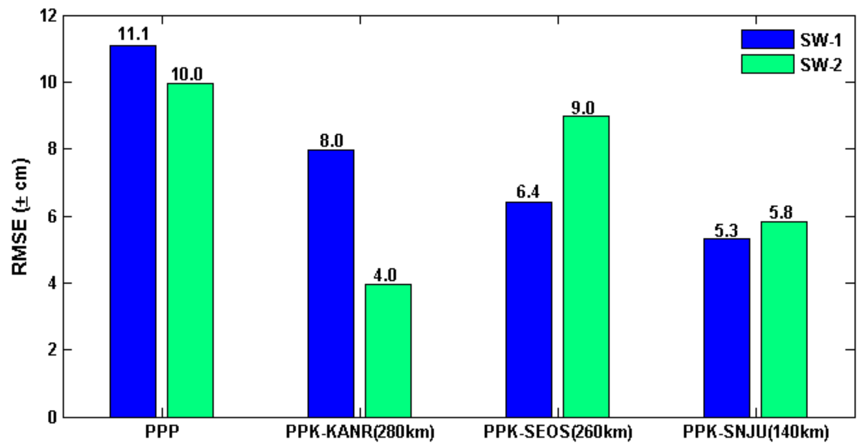

Fig. 10. RMSE of the GNSS-derived heights of the turntable test.

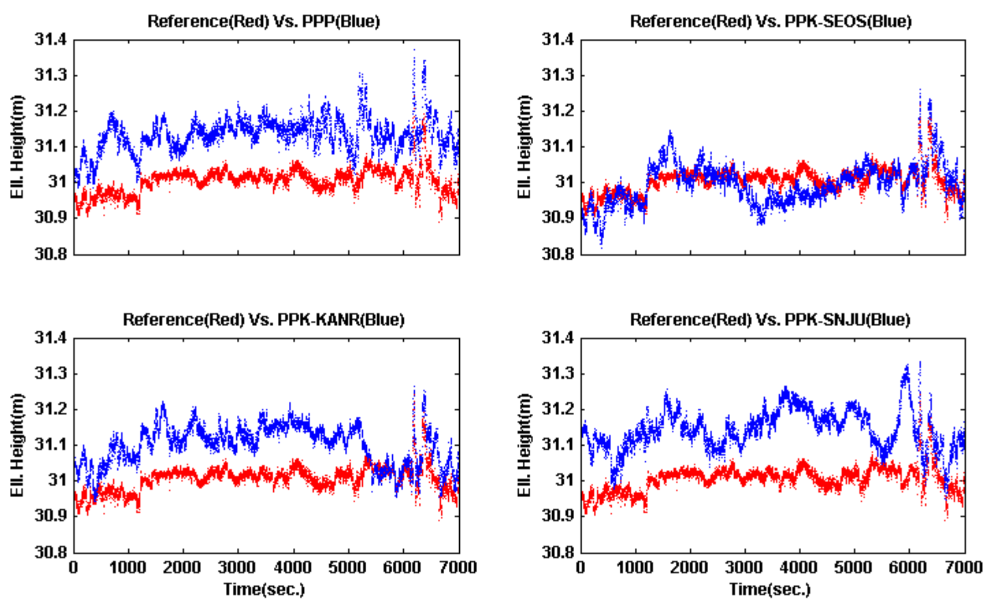

Fig. 11. Example of time series of the reference (red colored) and the GNSS-derived heights (blue colored) of the survey vessel test, which is results of the ANT-01 processed by SW-1.

SW-1 correlates the baseline lengths, whereas that of the SW-2 are free from them. Although an attempt was made to investigate further, it was not possible to draw a meaningful conclusion due to the fact that the number of size the observable sample was limited in the test. As a consequence of the turntable kinematic trial in this study, achievable accuracy of the height estimation by the PPP the medium-range PPK can be accessed to be no less than ±11.1 cm with 1-σ confidence level.

4.2.2 Survey vessel

The time series of the ellipsoidal heights of the ANT-01 are shown in Fig. 11; these results are obtained from the SW-1. Although the others are not presented there, their trend is similar to the ones given in the figure. As aforementioned, the medium-range PPK processed the vessel's GNSS measurements three times with the different reference stations. In these graphs in the figure, although precision of these solutions are somewhat comparable with the reference values, biases are observed, except for the PPK with SEOS. According to Beutler et al. (1987), the troposphere is the main error sources of the GNSS height determination, especially relative tropospheric delay for the relative positioning, whereas the ionosphere impact into the baseline estimation. Since the ionospheric-free (L3) measurements are used in the PPP to gain positional solutions, only the residual error is the troposphere. On the other hand, even if both of the atmospheric errors are estimated in the medium-range PPK, their residual errors exist in the solutions. Consequentially,

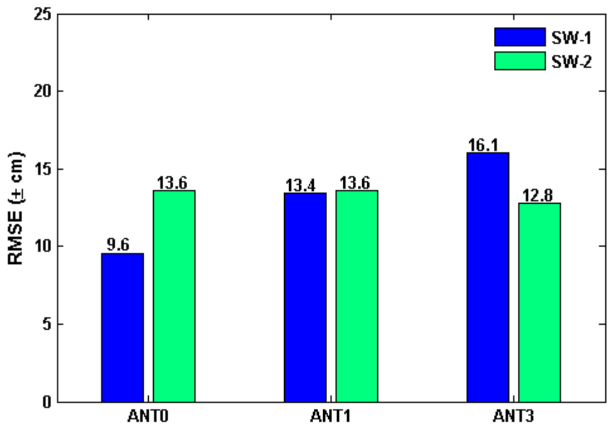

Fig. 12. RMSE of the GNSS PPP-derived ellipsoidal heights of the survey vessel test.

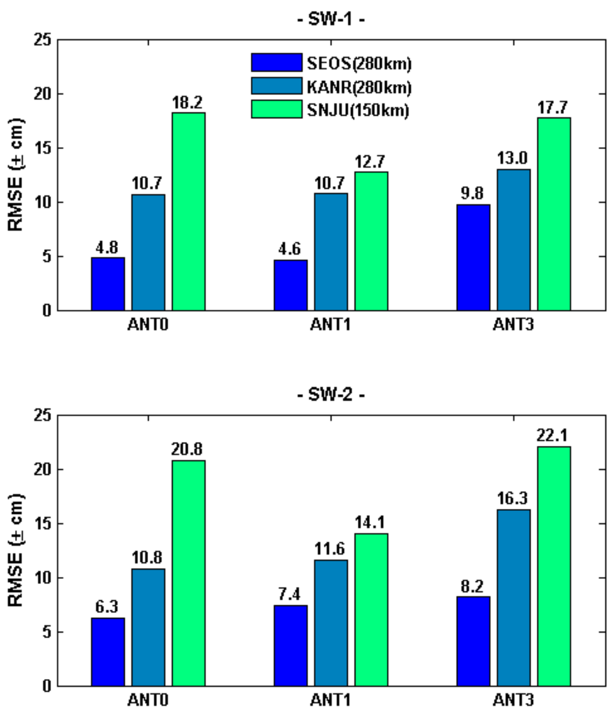

Fig. 13. RMSE of the GNSS medium-range PPK-derived heights of the survey vessel test.

considering the GNSS errors' contribution to the height determination, the biases in Fig. 11 are perhaps introduced by the residual tropospheric delay.

Fig. 12 manifests RMSEs of the GNSS PPP-derived ellipsoidal heights of the survey vessel test. Whilst these values of the SW-1 range from ±9.6 to 16.1 cm, those of the SW-2 are relatively consistent around ±13 cm. This discrepancy is probably caused by a quality control and estimation algorithm adopted by each the software. RMSE values of the medium-range PPK estimated heights are provided in Fig. 13. Comparing to Fig. 12, the PPK results heavily depends upon selection of the reference station. For example, the values of ANT-0 from the SW-1 are ±4.8 cm with respect to SEOS, but ±18.2 cm against SNJU, indicating that the shortest baseline results in the worst accuracy. In order to understand this reason, meteorological parameters (e.g. temperature and humidity) has been examined from Korean metrological agency's database, which reveals that the condition of the testing area is most similar to SEOS, but far different from SNJU. For example, it was heavily clouded with high humidity at the testing, but sunny in the SNJU; hence amount of the relative tropospheric delay exists largely even if the DD technique is applied. It can be figured out at the end that the accuracy of the height determination from the medium-range PPK relies on the reference used for DD modelling because of the residual relative tropospheric delay. In addition, a comparison of the different software usage in the PPP uncovers that the SW-1 provides slightly better solution in term of the RMSE.

As a consequence of the vessel test with multiple GNSS receivers, some conclusion are derived as: (a) the PPP-derived vertical solutions are more consistent than those of the PPK that heavily depends a reference station; (b) accuracy of the PPP-solution obtained from the two software is almost equivalent, but the SW-2 is more stable; (c) achievable accuracy with 1-σ confidence level of the PPP-estimated heights is better than ±16.1 cm, whereas that of the medium-range PPK is around ±4 to 23 cm.

5. CONCLUSIONS

Adaptation to the future employment of the ERS concept in Korean hydrographic society, the CPH-based GNSS positioning techniques, such as the PPP and the medium-range PPK, have been tested in terms of accuracy (i.e. RMSE against the published and the short-range PPK-derived ellipsoidal heights) on static and kinematic mode by using the two software packages. Performance of the two packages is comparable in both the CPH-based techniques as the accuracy differs only few centimetres level. Although results of the static test is more accurate than those of the kinematic, it is somewhat overestimated because temporal residual tropospheric delay for 24 hours evened out in the RMSE computation. Comparing the medium-range PPK to the PPP, the latter's accuracy is more consistent, and that of the former varies against selection of the reference station. As a consequence of these tests, achievable accuracy of the PPP with 1-σ confidence level is better than ±16.1 cm, whereas that of the medium-range PPK is no less than ±22.0 cm; these accuracy enable to fulfil the 1st order hydrographic surveys of IHO S-44 guidelines even (i.e., Table 1) if the other uncertainties related to height transformation and depth observation are considered. Nevertheless, since the experiments performed in this study are limited to the number and the size of testing samples, more intensive analysis under various survey conditions are highly recommenced in future for more reliable accuracy assessment.

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