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DETERMINATION OF VERTICAL DATUM LEVEL FOR TIDAL BENCH MARK USING GNSS BUOY OBSERVATIONS

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Key words: vertical datum, tidal benchmark, GNSS, buoy.

ABSTRACT

Coastal areas are the most vulnerable areas to sea level fluctuations. Such areas comprise approximately 4% of South Korea's total land; therefore, monitoring these fluctuations is crucial. The present study determined the vertical datum level using a global navigation satellite system (GNSS). Unlike traditional sea level measurements, which are performed using fixed-type gauge observations, a GNSS has an accuracy of a few millimetres and no spatiotemporal constraints. For this purpose, a set of buoys containing GNSS devices was installed in coastal waters, and observations were performed for more than 8 h. The processed GNSS buoy data were compared with tidal measurement data to determine their accuracy. The study results indicated that it is possible to efficiently obtain height information in coastal areas that are far from land using GNSS buoys. Furthermore, the limitations of traditional methods regarding long-term continuous observations can be overcome.

I. INTRODUCTION

In recent years, sea levels worldwide have changed continuously owing to rising seawater temperatures. In South Korea, an increasing number of civil engineering projects are being undertaken in coastal areas through land reclamation projects (Roh et al., 2016). As a result, accurate water level reference points and height information are specifically required for the vast and complex waters off the west coast, which have considerable tidal differences, for ensuring the safe passage of ships and the safety of coastal developments (Cho et al., 2003).

Tidal bench mark (TBM) results, obtained and announced by the Korea Hydrographic and Oceanographic Agency (KHOA), are generally used to acquire information on ocean height. These results are crucial for ocean depth sounding and determining maritime and coastal constructions (Lee et al., 2013). TBM heights are usually obtained by determining the location and level of the datum level (DL), which indicates the height difference between the sea level and the DL. In levelling, the height of the determined DL is set to '0' and the height from the DL to the TBM installed on land is calculated. This is referred to as the tidal gauge observation (Bisnath et al., 2003). However, errors may occur depending on the operator's proficiency and observation time limitations (Dawidowicz, 2014), and it is impossible to conduct observations at sea when it is far from the land because gauge observations target the continuously fluctuating sea surface rather than the stationary DL after the gauge measurement is fixed (Hein et al., 1992).

The present study investigated the vertical DL of the western coastal waters of South Korea using a global navigation satellite system (GNSS). To conduct this study, GNSS buoys that could be set afloat in the sea to observe the sea level were constructed. Six sites around three islands and three coastal areas - areas where the tidal differences are large and complex - were selected for investigation, and the sea level was observed. The GNSS buoy results were interpreted through comparisons with existing tidal and gauge observations.

II. STUDY AREA AND METHOD

1. Study Area

To compare and verify data obtained using GNSS buoys, six sites were selected; of these, three were at Boryeong-si, Chungcheongnam-do, and three were at Gunsan-si, Jeollabuk-do. At these sites, hydraulic tidal and gauge observations were employed (Fig. 1).

2. Method

To calculate the exact position of a GNSS buoy using the post-processed kinematic (PPK) positioning method, datum point

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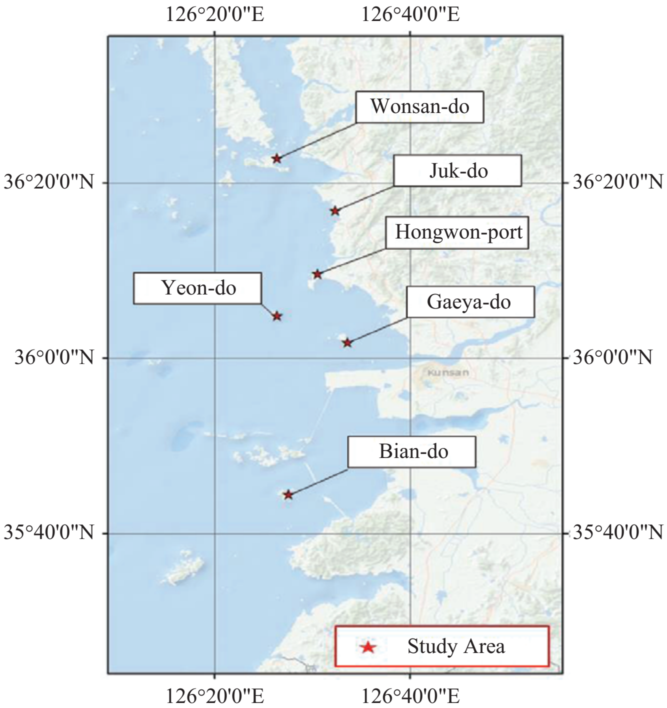

Fig. 1. Study areas.

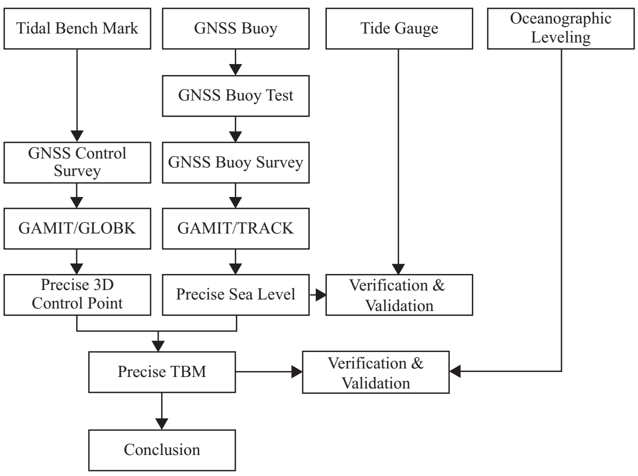

Fig. 2. Workflow of study.

measurements should be made simultaneously at adjacent datum points (Chen et al., 2004; Cho et al., 2015). Accordingly, three datum points near the three study sites were selected. Three-dimensional position coordinates were calculated using the precision processing software GAMIT/GLOBK (Herring et al., 2011). To analyse the GNSS buoy data obtained at 10 s intervals, GAMIT/TRACK was used (Shih et al., 2006). The sea level changes were confirmed through a comparative analysis of the final calculations of the GNSS buoy observation results, and the results were obtained using a hydrographic tide gauge. Finally, the TBM height determined through levelling was analysed and compared with the height obtained through the interpretation of the GNSS buoy observation results. Fig. 2 illustrates the workflow of the study.

Fig. 3. GNSS observation at a datum point.

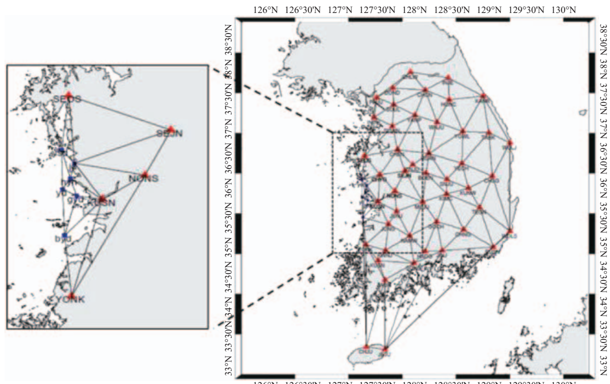

Fig. 4. Distribution of nationwide network for data processing.

III. GNSS OBSERVATION PROCESSING

1. GNSS Datum Point Measurement

A height determination using the GNSS buoys was conducted based on the precise relative height difference between the sea surface and TBM; thus, precise three-dimensional results of the accurately fixed TBM were required because the PPK interpretation of the GNSS buoys' location on the sea surface is affected by the precision of the datum point measurements (Kang, 2013). For the GNSS datum point observations, the satellite mask angle was 15° or higher, the phase centre was used as the reference height, the data acquisition interval was set at 10 s, and observations were made for more than 8 h. Fig. 3 displays the setup for the GNSS observation at 09:00 AM on June 18, 2016.

To execute reliable network adjustments with precise TBM results, baseline analyses of the data obtained from nationwide permanent observation stations were conducted using GAMIT (Herring et al., 2010). For the same time duration, network adjustments were performed by connecting the adjacent five permanent observation stations using the GLOBK software (Fig. 4). For the data processing in GAMIT, five permanent observation stations near the observation point were linked with the baselines, which are actually the 41 national permanent observation stations. The data were interpreted for each session, and the out-

Table 1. 3D coordinates obtained using GAMIT/GLOBK software.

Study Area	X	Y	Z	Latitude	Longitude	Ellipsoid Height
Wonsan-do	-3053667.18	4136299.48	3761881.62	36.38	126.44	27.72
Juk-do	-3064958.12	4136176.94	3752884.83	36.28	126.54	28.26
Hongwon-port	-3067056.78	4143962.52	3742638.02	36.16	126.51	29.2
Yeon-do	-3065709.91	4151402.97	3735534.94	36.08	126.44	28.03
Gaeya-do	-3075708.51	4148001.58	3731122.93	36.03	126.56	28.91
Bian-do	-3080292.16	4168649.30	3704412.60	35.74	126.46	28.32

comes were adjusted based on all 41 permanent observation stations by using initial fixed coordinates. The three-dimensional precision outcome obtained using the GAMIT/GLOBK software after the GNSS observations is presented in Table 1, and the calculated results were used as datum points for PPK interpretation after the GNSS buoy observation.

2. GNSS Buoy Survey

GNSS buoy observations were conducted on the first and 14th day of the lunar calendar, when the tidal difference is considered to be greatest, and the datum surveys was simultaneously conducted for PPK interpretation for 8 h or more per observation, 16 times in six months. The GNSS buoys were set up within 10 km of a datum point. The reception interval was set at 10 s, the mask angle was set to 15°, the phase centre was used as the reference height, and observations were conducted using the GNSS in combination with the buoys. At a short distance from the coastline of the harbour where vessel movements and waves are minimal, a GNSS buoy was placed. This minimised errors that can occur due to waves tilting the buoy and multipath and reception blocking of the GNSS signal reflected from nearby structures and vessels. Analyses were performed at places near to where the hydraulic tide gauge observations were made to enable accurate comparison between the two sets of observations (Fig. 5).

Fig. 5. GNSS buoy observation.

3. GNSS Buoy Data Processing

The participants of the present study interpreted the movements of the GNSS buoys from the reference point using the PPK method. For PPK analysis, GAMIT/TRACK software developed at the Massachusetts Institute of Technology for kinematic positioning analysis was used, and the observation data were analysed using the precise ephemeris that was published approximately two weeks from the observation date by the international GNSS service for precise analysis. The analysis results using GAMIT/TRACK were obtained by removing outliers that were greater than 95% of the confidence level by using the residuals against the mean, and the calculated results were averaged in 10-min units for comparison with the results obtained using the hydraulic tide gauge. The coefficient of determination (R^2) of the trend line, which indicates the level of agreement among the analysis results obtained using GAMIT/TRACK, estimated values, and actual data, was equal to 0.9922, and the coefficient of determination after removing outliers greater than two standard deviations after processing the data using GAMIT/TRACK was 0.9993.

IV. COMPARATIVE ANALYSIS

1. Comparative Analysis of GNSS Buoy and Hydraulic Tide Gauge Data

This study acquired hydraulic tide gauge observation data for the research sites from the KHOA; the obtained data were assumed to be the true values and were compared with the results obtained through PPK analysis after GNSS buoy investigations of tidal levels using the averages, standard deviations of errors, and correlation analyses.

The comparison and analysis results for the six research sites are presented in Table 2 and indicate that the smallest average difference between the hydraulic tide gauge and GNSS buoy observation results was identified at Wonsan-do, being 0.264 cm, whereas the largest difference was reported at Bian-do, being 4.143 cm. The average of the standard deviations of the errors between the hydraulic tide gauge and GNSS buoy observations was 3.632 cm. The average of the correlation coefficients obtained from the correlation analysis was 0.9993, which indicated that the tidal level fluctuations observed using the hydraulic tide gauge and GNSS buoys at all research sites were almost identical.

3. Comparison of TBM Results

To test whether GNSS buoy observations can replace gauge observations, the TBM height data from the DL of the research sites, as determined through gauge observations during the six months of observation, were acquired with the help of the KHOA

Table 2. Results of observations of all study areas.

Study area / Observations		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Juk-do	Tide gauge average (cm)	2453.4	2362.6	2356.7	2370.7	2325.9	2361.1	2235.9	2411.2	2271.1	2337.0	2418.6	2235.3	2407.2	2180.8	2249.8	2371.4
	GNSS buoy average (cm)	2451.2	2365.3	2358.1	2369.4	2325.7	2362.8	2234.7	2411.9	2271.6	2343.2	2418.7	2237.9	2407.2	2184.8	2251.3	2376.6
	Correlation coefficient (R^2)	0.9998	0.9998	0.9999	0.9994	0.9998	0.9981	0.9993	0.9994	0.9980	0.9998	0.9981	0.9997	0.9971	0.9997	0.9986	1.0000
	Std. Dev. of the errors (cm)	4.644	5.064	3.014	6.202	4.403	5.187	5.095	5.149	7.126	3.318	4.667	3.714	4.922	2.814	4.803	2.977
Hongwon-port	Tide gauge average (cm)	2348.0	2320.9	2284.9	2280.6	2199.5	2371.3	2274.4	2363.6	2347.5	2459.6	2387.5	2224.1	2246.6	2211.5	2221.8	2286.1
	GNSS buoy average (cm)	2350.3	2327.2	2286.3	2287.0	2199.1	2374.3	2271.3	2365.7	2344.4	2462.5	2386.5	2226.9	2245.8	2214.3	2220.2	2288.7
	Correlation coefficient (R^2)	0.9999	1.0000	1.0000	1.0000	0.9990	0.9998	1.0000	0.9998	1.0000	0.9993	0.9990	1.0000	0.9999	1.0000	0.9998	1.0000
	Std. Dev. of the errors (cm)	3.640	1.288	4.810	1.511	5.161	1.938	0.494	3.943	1.231	3.816	3.387	0.630	5.799	0.108	4.665	0.144
Yeon-do	Tide gauge average (cm)	2347.1	2402.3	2405.0	2375.6	2335.2	2421.4	2231.1	2417.9	2338.9	2348.3	2436.4	2244.5	2410.8	2315.0	2256.3	2452.8
	GNSS buoy average (cm)	2343.2	2407.0	2405.0	2374.3	2337.1	2426.8	2233.9	2427.0	2333.6	2350.2	2434.9	2248.5	2408.6	2318.4	2260.0	2456.4
	Correlation coefficient (R^2)	0.9999	1.0000	1.0000	0.9997	1.0000	0.9991	0.9991	0.9998	0.9993	0.9998	0.9975	0.9996	0.9979	0.9998	0.9991	0.9999
	Std. Dev. of the errors (cm)	2.521	1.103	4.219	4.653	0.818	3.456	5.023	2.900	6.384	5.134	4.114	3.848	4.898	3.156	3.453	2.735
Wonsan-do	Tide gauge average (cm)	2195.7	2273.8	2378.9	2254.1	2240.9	2348.7	2223.9	2380.4	2251.5	2363.6	2366.8	2170.8	2364.5	2235.6	2336.7	2307.0
	GNSS buoy average (cm)	2196.3	2274.3	2377.5	2255.0	2240.5	2342.8	2222.2	2379.0	2252.3	2361.9	2364.8	2173.9	2362.6	2240.3	2339.1	2306.2
	Correlation coefficient (R^2)	0.9995	0.9997	0.9996	0.9997	0.9995	0.9998	0.9997	0.9995	0.9998	0.9997	0.9999	0.9995	0.9981	0.9994	0.9993	1.0000
	Std. Dev. of the errors (cm)	4.759	4.409	3.712	4.031	4.326	2.708	4.542	4.521	2.819	4.213	2.641	4.252	4.844	7.753	4.164	1.577
Gaeya-do	Tide gauge average (cm)	2398.2	2436.5	2406.7	2416.1	2451.1	2251.2	2428.8	2330.3	2388.8	2458.9	2278.4	2421.5	2344.1	2402.9	2406.4	2518.9
	GNSS buoy average (cm)	2394.1	2437.1	2407.0	2416.1	2450.7	2253.6	2430.9	2332.7	2391.2	2460.0	2280.7	2423.7	2347.9	2406.3	2410.0	2523.0
	Correlation coefficient (R^2)	0.9999	0.9996	0.9996	0.9997	0.9993	1.0000	1.0000	1.0000	1.0000	0.9990	1.0000	1.0000	1.0000	1.0000	0.9997	0.9997
	Std. Dev. of the errors (cm)	4.121	4.228	5.481	6.806	4.049	0.186	0.647	0.133	0.095	4.708	0.048	0.234	1.399	1.400	4.100	3.839
Bian-do	Tide gauge average (cm)	2263.4	2312.2	2332.6	2205.6	2343.8	2223.4	2334.1	2214.0	2298.1	2326.0	2113.6	2346.2	2240.3	2177.8	-	-
	GNSS buoy average (cm)	2177.8	2273.5	2327.5	2352.8	2211.4	2360.1	2237.8	2348.3	2231.6	2306.0	2336.2	2133.2	2360.5	2259.3	2193.3	2299.8
	Correlation coefficient (R^2)	1.0000	0.9936	1.0000	1.0000	1.0000	0.9997	0.9971	0.9987	0.9994	0.9951	0.9996	0.9916	0.9999	1.0000	-	-
	Std. Dev. of the errors (cm)	0.221	11.203	1.043	1.242	0.283	4.554	8.064	6.870	5.572	8.503	2.468	6.244	2.654	2.640	-	-

Table 3. Comparison of heights obtained from GNSS and tangential observations.

Study area	Height using GNSS Buoy observations (cm)	Height by tangent observation (cm)
Wonsan-do	834.7	825.8
Juk-do	919.9	913.1
Hongwon-port	815.6	824.6
Yeon-do	731.2	724.1
Gaeya-do	872.8	867.5
Bian-do	574.9	558.8

of the Ministry of Oceans and Fisheries. If GNSS buoy observations and gauge observations were performed simultaneously, a comparison between their results was possible.

However, this study determined the TBM height by calculating elevation differences for each research site by using the difference between the ellipsoidal height of the TBM and the ellipsoidal height calculated from the GNSS buoy observations, and by adding the height from the DL to the sea level that was observed using the hydraulic tide gauge. Comparisons and analyses of the GNSS buoy observations and gauge observations were conducted assuming that the height between the DL and TBM was the true value. Table 3 presents the TBM heights determined through combining gauge observations and GNSS buoy observations, and demonstrates that the height obtained from the gauge observations at the Hongwon-port research site was 9 cm higher than that obtained from the GNSS buoy observations; by contrast, the heights at the five other research sites were 6.8-7.1 cm taller when obtained from GNSS buoy observations. The current method for determining the TBM through tidal observations uses the annual correction factor, and although accurate differences between the two tidal observation methods were not known because the correction factor had been

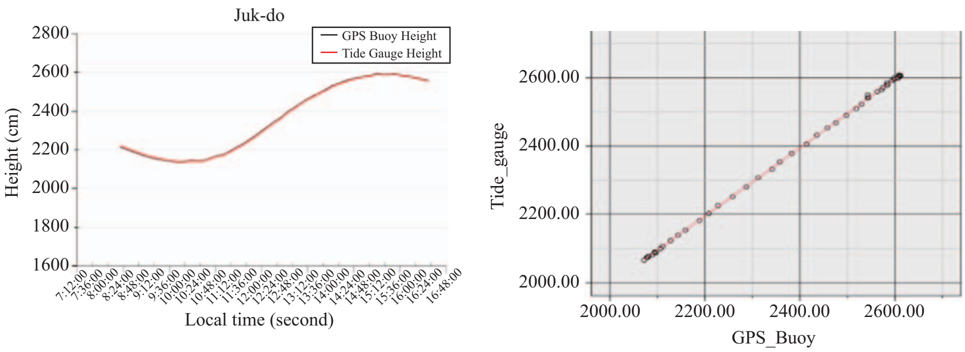

Fig. 6. Graph (left) and correlation (right) of tidal gauge and GNSS buoy result at Juk-do.

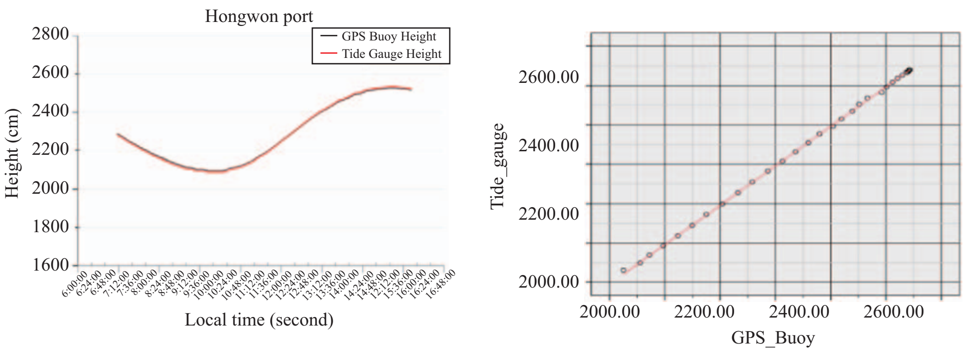

Fig. 7. Graph (left) and correlation (right) of tidal gauge and GNSS buoy result at Hongwon-port.

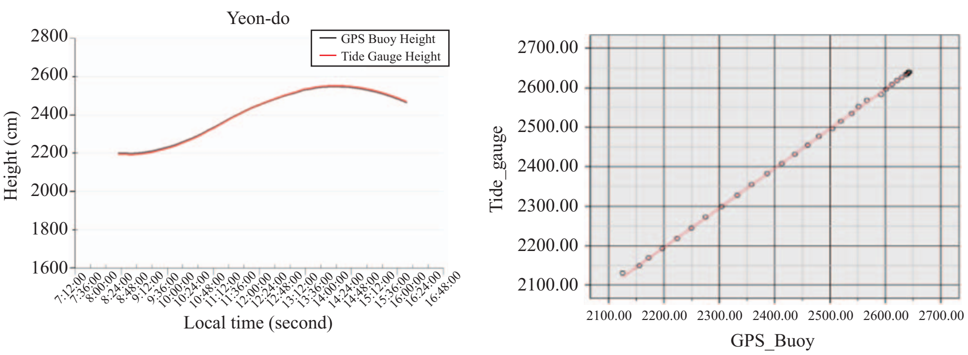

Fig. 8. Graph (left) and correlation (right) of tidal gauge and GNSS buoy result at Yeon-do.

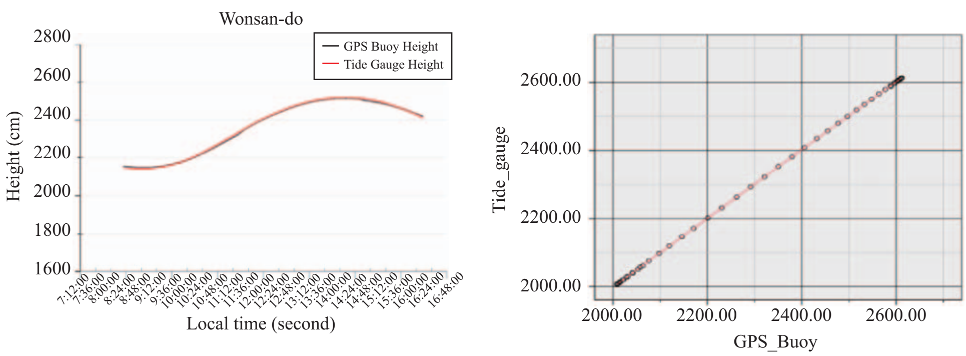

Fig. 9. Graph (left) and correlation (right) of tidal gauge and GNSS buoy result at Wansan-do.

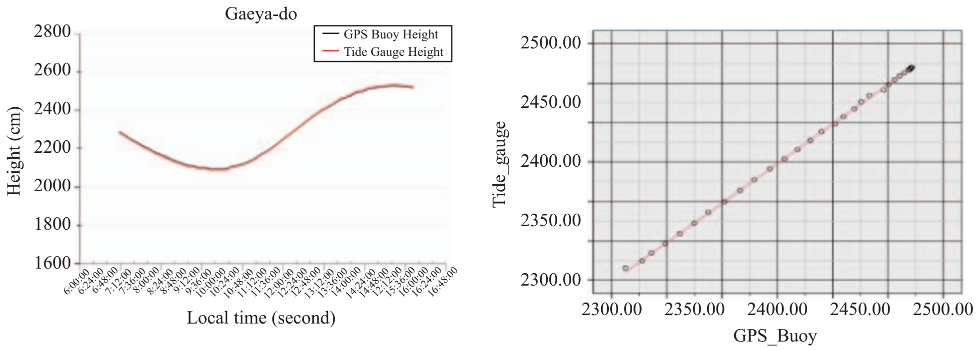

Fig. 10. Graph (left) and correlation (right) of tidal gauge and GNSS buoy result at Gaeya-do.

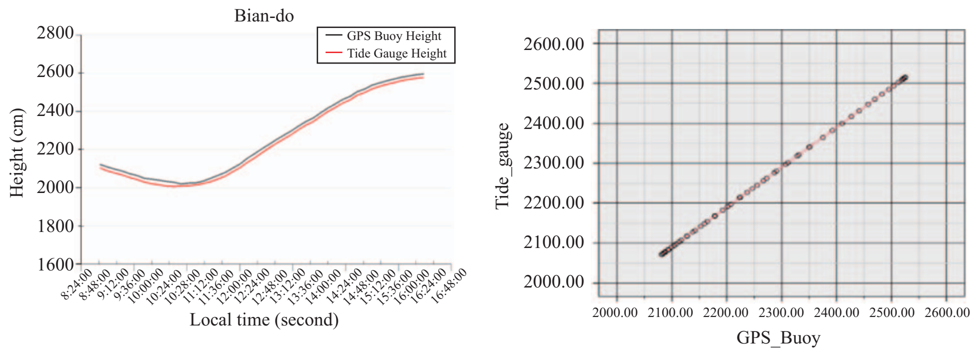

Fig. 11. Graph (left) and correlation (right) of tidal gauge and GNSS buoy result at Bian-do.

applied to the data already acquired, the differences were within 10 cm for all research sites.

Figs. 6-11 present plots of sea levels as observed for 8 h and their comparison with each tidal gauge measurement.

V. CONCLUSION

In the present study, observations were performed using GNSS buoys, which can float in seawater, placed at six selected research sites to determine TBMs. After observations were conducted, the data were processed using the PPK method and ±2σ was applied to the averages to obtain the results. These were then compared with those of the existing method and analysed, and the following conclusions were drawn:

(1) The comparative analysis of the GNSS buoy and hydraulic tide gauge observation results demonstrated that the minimum average difference was 0.831 cm (at Hongwon-port) and the maximum average difference was 1.686 cm (at the Yeon-do research site). In general, the average difference between the two values was less than 2 cm. The analysis of the standard deviations of the differences between the results obtained from both sets of observations indicated an average difference of 3.576 cm with a maximum and minimum difference of 4.464 cm and 2.633 cm, respectively. A correlation analysis revealed that the maximum and minimum correlation coefficients were 0.9997 and 0.9992, respectively, and the average coefficient was 0.9994, indicating a close relationship between the sea level fluctuations observed using the two sets of equipment.

(2) A comparison of the height calculations obtained using the TBM and the DL of the research sites through the results of GNSS buoy observations and tide gauge observations revealed a minimum difference of 0.9 cm (for Hongwon-port) and a maximum difference of -6.8 cm (for Juk-do). The difference was less than 10 cm at all research sites; thus, if a GNSS buoy is used instead of tide gauge observations, the TBM can be determined within a 10 cm margin of error.

(3) If GNSS buoy equipment is used to replace gauge observations, the quality and storage convenience of the observation data can be enhanced because spatiotemporal constraints can be resolved. Employing GNSS buoys enables observations to be conducting at any time without restrictions and in places where observations are otherwise difficult to perform, such as at a large distance from land.

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