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Original article

Accuracy Analysis of GNSS-derived Orthometric Height in Mountainous Areas

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Abstract

Recently, GNSS (Global Navigation Satellite System)-derived orthometric height determination has been studied to improve the time and cost-effectiveness of traditional leveling surveying. However, the accuracy of this new survey method was evaluated when unknown points are located lower than control points. In this study, the accuracy of GNSS-derived orthometric height was examined using TPs (Triangulation Points) to verify the stability of surveying in mountainous areas. The GNSS survey data were obtained from Mungyeong, Unbong/Hadong, Uljin, and Jangseong. Three unknown points were surrounded by more than three UCPs (Unified Control Points) or BMs (Benchmarks) following the guideline for applying GNSS-derived orthometric height determination. A newly developed national geoid model, KNGeoid17 (Korean National Geoid 2017), has been applied for determining the orthometric height. In comparison with the official orthometric heights of the TPs, the heights of the unknown points in Mungyeong and Unbong/Hadong differ by more than 20 cm. On the other hand, TPs in Uljin and Jangseong show 15–16 cm of local bias with respect to the official products. Since the precision of official orthometric heights of TPs is known to be about 10 cm, these errors exceed the limit of the precision. Therefore, the official products should be checked to offer more reliable results to surveyors. As an alternative method of verifying accuracy, three different GNSS post-processing software were applied, and the results from each software were compared. The results showed that the differences in the whole test areas did not exceed 5 cm. Therefore, it was concluded that the precision of the GNSS-derived orthometric height was less than 5 cm, even though the unknown points were higher than the control points.

Keywords : GNSS-derived Orthometric Height, Mountainous Area, Triangulation Point, Korean National Geoid 2017, GNSS Software

1. Introduction

As a modern surveying method, GNSS (Global Navigation Satellite System)-derived orthometric height determination has been introduced to improve the duration and cost-effectiveness of traditional spirit leveling. The orthometric height is determined by the difference between the ellipsoidal height using GNSS and the geoidal height from a precise local geoid model. This new method is attracting attention because GNSS has been widely used to determine the precise position of the control and unknown points, and precise geoid models are continuously being developed. Especially, it is a meaningful method for determining the continuous orthometric height between inland and islands; or the region where the local leveling network is not. For this reason, in many countries such as USA, Canada, and Japan, orthometric heights are determined using GNSS surveying and local geoid models when the target precision is 2–5 cm (NGS, 1997; ICSM, 2014; GSI, 2017).

Since 2012, the NGII (National Geographic Information Institute) started researching the precise geoid model development, and KNGeoid14 (Korean National Geoid 2014)

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with the 3.3 cm level of precision was determined in 2014 (NGII, 2014a). In addition, the initial version of a guideline for applying GNSS-derived orthometric height determination was introduced (NGII, 2014b). In 2017, pilot surveying was conducted as a part of the study on the construction of a national leveling network based on UCPs (Unified Control Points) in order to find way to improve precision in mountainous area. As a result, it was found that the highest points in the target area should be used, and at least one more control point is required when the height differences among the control and unknown points are more than 200 m (NGII, 2017b). Subsequently, the guideline was updated to the ver. 1.1 to reflect the above aforementioned conditions (NGII, 2017a).

Although some new conditions were added, there is still a limitation in mountainous areas. Because the guideline recommends the use of UCPs or BMs (Benchmarks) for control points, it is impossible to apply the two updated conditions when unknown points that are located at mountain tops are selected. The TP (Triangulation Point) is a representative case. As a control point to determine the horizontal position, TPs have been established in a homogeneous distribution over the whole country. On the other hand, BMs were installed along roadways to guarantee the efficiency of the survey, and UCPs were established in plain areas for efficient access by surveyors. Thus, most UCPs and BMs were at lower heights than the TPs. Because of these characteristics of the distribution of control points, previous studies were performed on the plain area where many control points having official products were available (Park and Jung, 2014; Shin *et al*., 2014; Lee *et al*., 2015; Jung *et al*., 2017b), or benchmarks were selected as unknown points in the mountainous area (Jung *et al*., 2017a; Lee *et al*., 2017). In addition, those studies focused on evaluating the reliability of the GNSS-derived orthometric height determination, so that multiple commercial GNSS post-processing software were neither used nor compared with each other.

In this study, the accuracy of the GNSS-derived orthometric height was evaluated in cases where the unknown points were located higher than the control points using GNSS survey data obtained on the TPs. The accuracy of the calculated heights of the TPs was compared to the official orthometric height published by NGII. In addition, multiple GNSS processing software were applied for data processing and their consistency was checked because the precision of the official products of the TPs are not as high as that of the UCPs or BMs.

2. Methodology

2.1. Test area and GNSS surveying

In 2014, KNGeoid14 was developed by fitting the gravimetric geoid to show a minimum difference with respect to the UCPs. Since many of the UCPs located in plain areas were applied, the local precision of the geoid model is generally more precise in plain areas than in mountainous areas. In this study, Mungyeong, Unbong/Hadong, Uljin and Jangseong, where the precision of KNGeoid is low, were selected as test areas. In each test area, three TPs were selected as unknown points and these points were surrounded by three control points (i.e., UCPs or BMs) following the guideline for GNSS-derived orthometric height determination. Because the TPs are generally located higher than the UCPs or BMs, the conditions set in the guideline could not satisfied. Instead, the UCP or BM located as high as possible in the test area was added. Fig. 1 shows the distribution of the unknown and control points in the test area, and the official orthometric heights of the unknown and control points are summarized in Table 1. In Fig. 1, the unknown and control points are plotted with red dots and blue triangles, respectively.

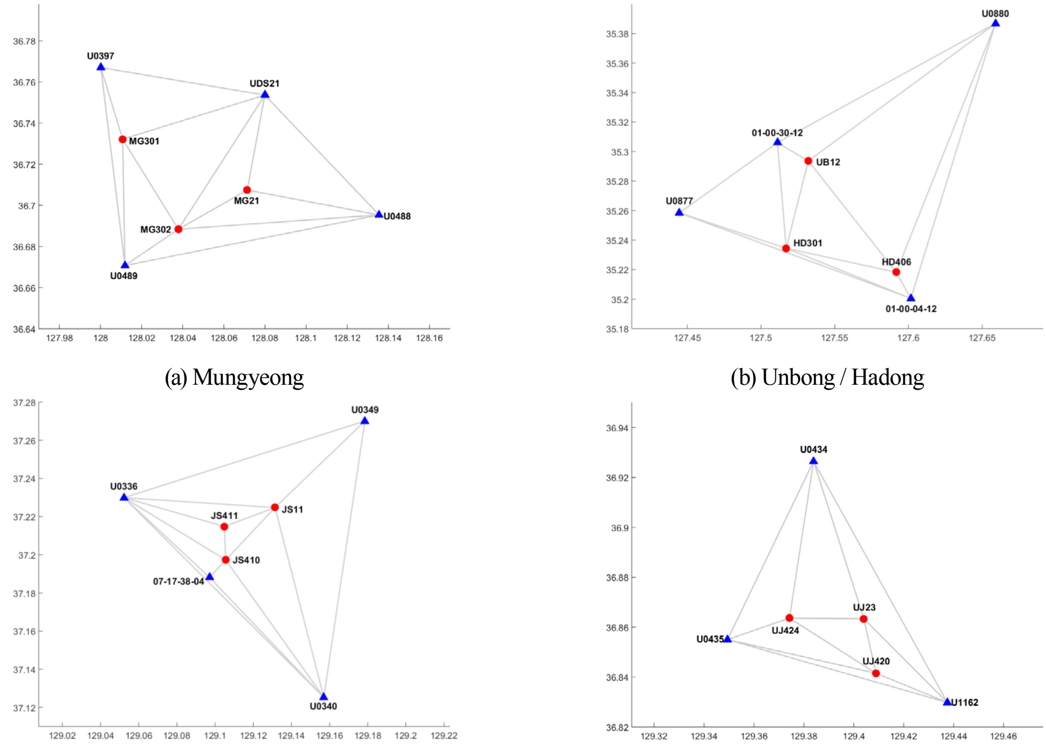
The features of the test areas are described next. In Mungyeong, the official orthometric heights of all TPs exceed 900 m, but the UCPs that were applied as control points were lower than 300 m in height. Thus, the control points were located in the plain area but the unknown points are at the top of the mountain. Although the highest control point (U0397) was added, the differences between the control and unknown points were still more than 700 m.

Among the four test areas, the highest unknown point was located in Unbong/Hadong. The official orthometric height of UB12 was about 1500 m and that of the other two unknown points were 540 and 750 m. Fortunately, the height of the benchmark (01-00-30-12) was about 1100 m so that it covered the other two unknown points. Thus, it was expected that the atmospheric effect would be estimated properly by fixing the benchmark point.

Similar to Mungyeong, the heights of unknown points in

Jangseong were more than 900 m. The height of the additional fixed benchmark (07-17-38-04) was 705 m, which seemed to reflect the characteristics of the mountainous variation compared to Mungyeong.

Because the entire unknown and control points in Uljin were located lower than 500 m, Uljin was not considered a mountainous area. However, the maximum difference between the control and unknown points was about 300 m, and the previous study pointed out the large error on the geoid model in Uljin. The accuracy of the GNSS-derived orthometric height depends on the geoid model; therefore, Uljin was also included among the test areas.



(a) Mungyeong

(b) Unbong / Hadong

(c) Jangseong

(d) Uljin

Fig. 1. Distribution of control and unknown points in the test areas

Table 1. Official products of control and unknown points (unit: m)

Test Area	Control Points				Unknown Points		
Mungyeong	U0488	U0489	UDS21	U0397	MG301	MG302	MG201
	151.654	186.389	207.918	230.701	913.603	992.042	1063.562
Unbong/ Hadong	01-00-04-12	U0877	U0880	01-00-30-12	HD406	HD301	UB12
	21.387	66.954	314.514	1090.650	542.553	750.417	1502.894
Jangseong	U0430	U0349	U0336	07-17-38-04	JS411	JS410	JS11
	167.957	207.647	265.642	705.890	942.157	1158.530	1268.529
Uljin	U1162	U0434	U0435	-	UJ420	UJ23	UJ424
	10.430	21.100	94.180	-	275.563	417.869	432.566

Table 2. GNSS data processing strategy

		LGO	TBC	GIODIS
Manufacturer		Leica	Trimble	Javad
Version		8.2	2.70	-
Atmospheric Model	**Ionospheric**	Automatic	automatic	automatic
	Tropospheric	Computed	Modified Hopfield	Estimated using meteodata
Others	**Mask angle [deg]**	15	15	15
	Ephemeris	IGS	IGS	IGS
	Phase Center Variation	IGS	IGS	IGS

In accordance with the guideline, two days of GNSS surveying was necessary considering the geometry of satellites when the target accuracy is 3 cm. The observation duration was 4 hours, and the observation interval was less than 30 seconds. In this study, GNSS surveying was conducted following the guideline, and the observation interval was set to 15 seconds to guarantee stability in the mountainous area. The elevation mask angle was 15°.

2.2 GNSS processing strategy

In this study, the LGO (Leica Geo Office), TBC (Trimble Business Center), and GIODIS which were developed by Leica, Trimble, and Javad, respectively, were applied for the GNSS data processing and compared with each other. For the scientific GNSS software (i.e. Bernese, GIPSY-OASIS (GNSS-Inferred Positioning System and Orbit Analysis Simulation Software), GAMIT (GNSS At MIT)), users set up various options including outlier detection criteria, atmospheric models, and mapping functions without restraint. On the other hand, commercial manufacturers tend to develop GNSS processing strategy and software based on their longstanding experience. Therefore, only a few options, such as ionospheric and tropospheric models, could be selected, and other detailed strategies were hidden. In this study, default processing options were set up for each software. For the LGO, “Computed” was selected for the tropospheric error estimation because Leica recommends using this option when the baseline is longer or the height difference is large. In the “Computed” mode, the tropospheric error is calculated based on the modified Hopfield model, and the residuals are estimated using control stations. In the case of the GIODIS, it estimates the troposphere delay using the global spread meteodata considering the geographical location, height, observation date and time. For reference, Lee (2018) found that the tropospheric modeling scheme frequently produces a difference of more than 5 cm in the estimated ellipsoidal height. Thus, a few centimeters of height difference were expected due to the change in software. Other options were set up identically following the guideline; the mask angle was set to 15°, the ephemeris and phase center variation model were set as IGS (International GNSS Service) products. Table 2 shows the selected options for the GNSS processing in each software.

According to the guideline, the local precise geoid model is required to determine the orthometric height with a few centimeters of precision. In 2018, NGII developed the new local geoid model called KNGeoid17 using newly obtained gravity and GNSS/Leveling data since 2014 (NGII, 2018). To check the reliability of the geoid model, orthometric height errors were calculated as the difference between the official orthometric height and the calculated height. As shown in Table 3, the orthometric heights calculated using KNGeoid17 generally have smaller error than those based on KNGeoid14. In particular, about 14 cm of the largest error at 01-00-30-12 located in the Unbong/Hadong region decreased to 1.5 cm. Only three points, U0489 located in the Mungyeong, U0434 located in the Uljin and 07-17-38-04 located in the Jangseong show relatively larger error with the KNGeoid model due to the difference in the number and the distribution of GNSS/Leveling data which were applied for the geoid modeling. Therefore, the new KNGeoid17 model was applied for the GNSS-derived orthometric height determination.

Table 3. The orthometric height errors at the control points (unit: m)

Points		Official orthometric height	Calculated Height (ellipsoidal – geoidal)		Height Error	
			KNGeoid14	KNGeoid17	KNGeoid14	KNGeoid17
Mungyeong	U0397	230.701	230.751	230.722	0.050	0.021
	U0488	151.654	151.676	151.657	0.022	0.003
	U0489	186.389	186.398	186.378	0.008	-0.012
	UDS21	207.918	207.940	207.894	0.022	-0.024
				< absolute mean >	0.026	0.015
Unbong / Hadong	UHD15	21.387	21.352	21.356	-0.035	-0.031
	01-00-30-12	1090.650	1090.793	1090.665	0.143	0.015
	U0877	66.954	66.970	66.964	0.016	0.010
	U0880	314.514	314.555	314.497	0.041	-0.017
				< absolute mean >	0.059	0.018
Uljin	U0432	7.515	7.587	7.534	0.072	0.019
	U0434	21.100	21.071	21.044	-0.029	-0.056
	U0435	94.180	94.196	94.174	0.016	-0.006
	U1162	10.430	10.443	10.422	0.013	-0.008
				< absolute mean >	0.033	0.022
Jangseong	07-17-38-04	705.890	705.899	705.863	0.009	-0.027
	U0336	265.642	265.571	265.590	-0.071	-0.052
	U0340	167.957	167.885	167.887	-0.072	-0.070
	U0349	207.647	207.600	207.610	-0.047	-0.037
				<absolute mean>	0.050	0.047

3. Accuracy Analysis of GNSS-derived Orthometric Height

3.1. Evaluation with respect to the official products

Fig. 2 and Table 4 show the orthometric height errors of each GNSS processing software with respect to the official products and their absolute mean. The orthometric heights of the TPs were determined by a study on the GPS-leveling network adjustment project in 2008. According to the final report of that project, it was found that the orthometric heights at the temporary points (which were observed as a part of the spirit leveling survey) were fixed. After adjustment, the precision of the orthometric height of the TPs was reported as about 10 cm.

The height errors with respect to the official products on MG21, MG301, and MG302 located in Mungyeong are about 27, 49, and 57 cm, respectively. Since fixed control points in Mungyeong were distributed in the plain area, height errors exceeding 10 cm could appear when tropospheric errors are not compensated properly. Nevertheless, height errors of more than 20 cm on the unknown points are quite large. In addition, the difference ranges from 20 cm to 60 cm does not seem to be consistent, and the TP located on the highest position did not show the largest error. After the adjustment in 2008, some of the local leveling networks were re-observed or their official products were updated by the maintenance of leveling network project. Because the heights at the temporary points have not been updated since 2008, these large errors should not be attributed to the error of the official products of the TPs.

In Unbong/Hadong region, it was found that HD301 and HD 406 had height errors of about 44 and 57 cm, respectively. The highest point (UB12) had the largest error (80 cm). As shown in Table 3, KNGeoid17 was improved in the test area by including new gravity and GNSS/Leveling data. Thus, over 40 cm of errors on the unknown points could not be attributed to geoid model error. Similar to Mungyeong, the range of the difference was not consistent and the correlation between the height and its error was not found. For example, UB12 had the largest error but the second highest point (HD301) had smaller error than HD406. Thus, the reliability check of the official products of the TP in the Unbong/Hadong was also necessary.

The unknown points in Uljin had height errors ranging from 13 cm to 17 cm. Assuming that the height error of the official orthometric height is about 15 cm, each unknown point had mismatches of only 2 cm or 3 cm. Those differences fall within the range of GNSS-derived orthometric height errors. In previous studies, a local bias was found in the western and eastern region on the Taebaek mountains in comparison with the geoidal model and GNSS/Leveling data. To find the reason for more than 15 cm of local bias, the local leveling network in the test area must be checked.

In the Jangseong region, the heights on the unknown points, JS11, JS410, and JS411 were more than 900 m, which is similar to Mungyeong. Although the height differences in Jangseong were not as large as those in Mungyeong or Unbong/Hadong, they exceed the precision level of the TPs. The average height error for the three unknown points was 16 cm, which was similar to the local bias in Uljin. Subtracting this average from the height difference of the unknown points yields 7, 5, and 1 cm of residuals, respectively. Because the largest residual (7 cm) occurs at the highest point (JS11), it is doubtful that there is a local bias in the test area.

To sum up, the unknown points in Mungyeong and Unbong/Hadong had more than 20 cm in height errors, and the range of the differences exceeded 20 cm. Moreover, these errors are not strongly correlated with the height and the local characteristics of the geoid model; thus, the official orthometric heights of the TPs should be examined. Furthermore, the height error in Unbong/Hadong is as high as 80 cm, despite the update of geoid model. To confirm that the height error on the unknown points is a non-updated effect of the official products of the TPs, the newly conducted leveling network adjustment results and the history of the official orthometric height of the TPs should be checked. On the other hand, Uljin and Jangseong did not have huge differences with respect to the official products. However, there seems to be a local bias in the leveling network because the height differences in the test areas were relatively similar. Thus, it is necessary to check whether the height errors on the unknown points were propagated from the local leveling network or the official products were not updated.

3.2 Consistency check among GNSS post-processing software

As shown in Fig. 2 and Table 4, the height errors with respect to the official orthometric heights exceed 10 cm. Although the previous study indicates that the precision of the

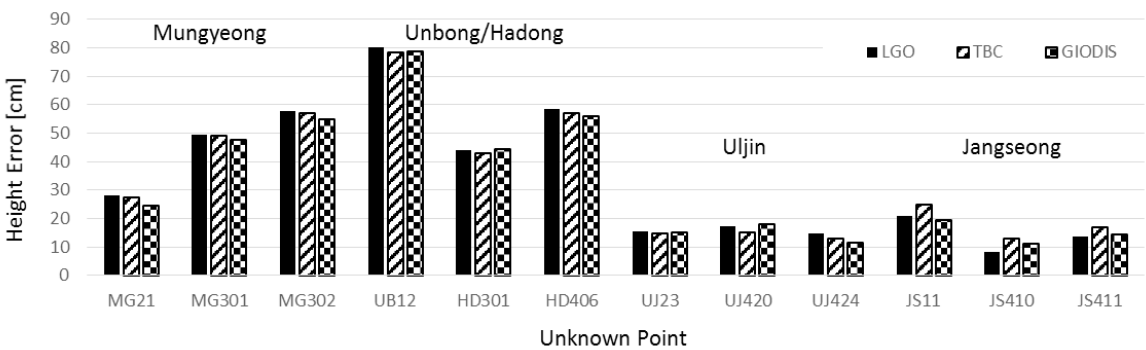


Fig. 2. Height errors with respect to the official orthometric heights

Table 4. Height error with respect to the official orthometric heights (unit: cm)

Test Area	Unknown Point	LGO	TBC	GIODIS	Abs. Mean
Mungyeong	MG21	-28.00	-27.50	-24.45	26.65
	MG301	-49.45	-49.00	-47.54	48.66
	MG302	-57.83	-57.20	-55.03	56.69
Unbong/Hadong	UB12	-80.05	-78.40	-78.78	79.08
	HD301	-43.90	-42.90	-44.35	43.72
	HD406	-58.52	-57.20	-55.79	57.17
Uljin	UJ23	15.28	14.60	15.10	14.99
	UJ420	17.36	15.10	17.84	16.77
	UJ424	14.63	12.80	11.63	13.02
Jangseong	JS11	-20.81	-24.70	-19.55	21.69
	JS410	-8.31	-12.80	-10.94	10.68
	JS411	-13.67	-16.90	-14.41	14.99

orthometric heights of the TPs is about 10 cm, the differences obtained in this study are relatively large. This means that the official orthometric height may not be suitable for use in evaluating the accuracy of the GNSS-derived orthometric height. Meanwhile, the processed results were different due to the model and software strategies despite using the same GNSS observation data and network design. Thus, if the differences among the calculated orthometric heights using different software are smaller than a few centimeters, it could be concluded that the GNSS-derived orthometric height has a few centimeters of precision in mountainous areas. Because three different GNSS post-processing software were applied to determine the heights of the unknown points in this study, the precision of the GNSS-derived orthometric height was evaluated based on the consistency of the processed results.

Fig. 3 and Table 5 show the difference between the processed results when the LGO was assumed to be true. In the Mungyeong region, the differences in the TBC and GIODIS with re spect to the LGO were less than 1 cm and 4 cm, respectively. Since the control points were located in the plain area and the height differences among the control and unknown points were more than 600 m, the estimated tropospheric error could be significantly different in the processing software. However, it was found that the maximum difference did not exceed 4 cm; thus, the GNSS-derived orthometric height in Mungyeong would be less than 5 cm.

Unlike Mungyeong, benchmark 01-00-30-12 was located near the top of the mountain. Although one unknown point (UB12) was higher than 01-00-30-12, other two unknown points were covered by highest control points, following the guideline in the mountainous areas. For this reason, the calculated orthometric heights on the unknown points had differences of less than 3 cm. In addition, since the height differences among the control and unknown points were not quite large (smaller than 300 m) in Uljin, the calculated results on the unknown points were limited to 3 cm.

The Jangseong test area had very large height differences between the control and unknown points. Although benchmark 07-17-38-04 was added to cover the unknown stations, differences of more than 500 m were obtained. These large height differences caused different tropospheric error estimations in the GNSS software such that the maximum difference between the LGO and TBC was 4.5 cm. Nevertheless, this difference did not exceed 5 cm; therefore, the precision of the determined height was concluded as 5 cm.

In this study, three different GNSS post-processing software were applied. Based on the comparison of the results, these software were not found to be identical because they included different atmospheric models and strategies. However, their height differences are limited to less than 5 cm. It should be noted that the control and unknown points were distributed in accordance with the guideline because the unknown points were located higher than the control points. Nevertheless, all the unknown points had less than 5 cm height differences despite using different software; thus, the results seem to be quite reliable. Therefore, it could be concluded that the 5 cm level of precision would be achieved through the GNSS-derived orthometric height determination technique in mountainous areas.

4. Conclusion

In this study, the accuracy of GNSS-derived orthometric heights in mountainous areas where the unknown points are located higher than the control points was evaluated. Four test areas (Mungyeong, Unbong/Hadong, Uljin, and Jangseong) were selected for this study. In these areas, three TPs were selected as unknown points, and they were surrounded by UCPs or BMs. The GNSS observation data were obtained

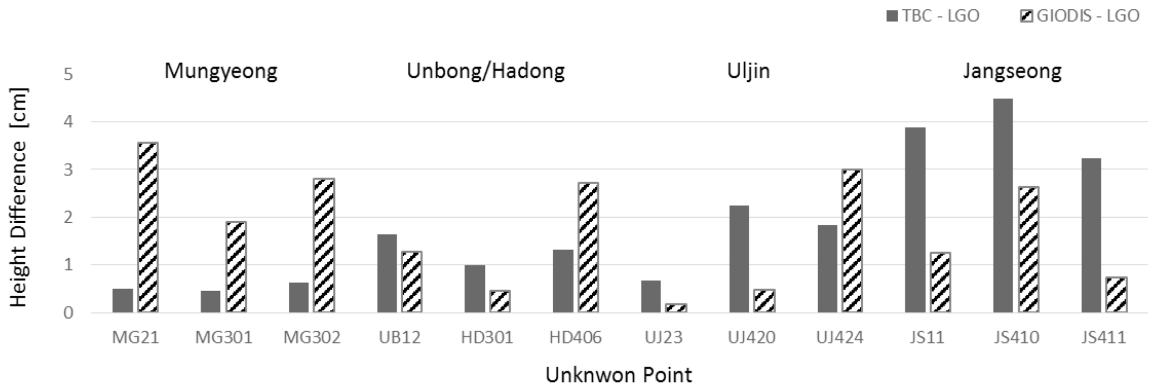


Fig. 3. Height differences among GNSS post-processing software

Table 5. Height difference among GNSS post-processing software (unit: cm)

Test Area	Unknown Point	TBC	GIODIS	Abs. Mean
Mungyeong	MG21	0.50	3.55	2.02
	MG301	0.45	1.91	1.18
	MG302	0.63	2.80	1.72
Unbong/Hadong	UB12	1.65	1.27	1.46
	HD301	1.00	-0.45	0.72
	HD406	1.32	2.73	2.02
Uljin	UJ23	-0.68	-0.18	0.43
	UJ420	-2.26	0.48	1.37
	UJ424	-1.83	-3.00	2.41
Jangseong	JS11	-3.88	1.27	2.58
	JS410	-4.49	-2.63	3.56
	JS411	-3.23	-0.74	1.99

following the guideline for applying GNSS-derived orthometric height determination, and the newly developed KNGeoid17 model was used to guarantee higher precision in the mountainous area. Furthermore, the LGO, TBC, and GIODIS were used for GNSS data processing and their results were compared to check for consistency.

The accuracy of the results was evaluated by comparing them to the official orthometric height of the TPs that were published by NGII. In the case of Mungyeong and Unbong/Hadong, all unknown points had more than 20 cm of height errors, and these errors were not correlated with the heights. On the other hand, the unknown points located in Uljin and Jangseong had mean height differences in the range 15–16 cm. The difference between GNSS-derived results and official products exceed the precision of the official orthometric heights (10 cm). After the determination of the official orthometric heights of the TPs in 2008, some local leveling network were re-observed and the results were updated. In addition, local bias in the leveling network in Uljin and Jangseong was noted. Therefore, the official orthometric heights of the TPs should be checked to verify the reason of large difference and to offer more reliable height of TPs for surveyors.

Since the GNSS-derived orthometric heights on the test area had errors of more than 10 cm with respect to the official products, the reliability of the results was re-checked by comparing the results from each GNSS post-processing software. For Mungyeong and Jangseong, the control points and unknown points had more than 500 m of height difference. Due to the different strategies of the GNSS post-processing software, the height differences in software was more than 3 cm. However, all unknown points did not exceed a difference of 5 cm. Considering that the unknown points were located higher than control points, the difference of less than 5 cm seemed quite consistent. Thus, the precision of the GNSS-derived orthometric heights on the mountainous area was estimated to be less than 5 cm. Because it was found that the orthometric heights of the TPs had more than 10 cm difference, the change in the heights of the TPs based on the GNSS-derived orthometric height determination method would be considered in future studies.

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