Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography
Vol. 36, No. 1, 1-8, 2018
https://doi.org/10.7848/ksgpc.2018.36.1.1

ISSN 1598-4850(Print)
ISSN 2288-260X(Online)
Original article

Accuracy Analysis of GNSS-derived Orthometric Heights on the Leveling Loop Disconnected Area

Jung, Sung Chae[1] · Kwon, Jay Hyoun[2] · Lee, Jisun[3]

Abstract

To compensate for the shortcomings of spirit leveling, research on the determination of GNSS (Global Navigation Satellite System)-derived orthometric height has been actively carried out. However, most analyses were primarily performed inland. In this study, the influences of the arrangement of control points, observation duration, and geoid model on the accuracy of the GNSS-derived orthometric height have been analyzed to suggest the proper method to apply the determination of GNSS-derived orthometric height to the leveling loop disconnected area. As a result, it was found that two known points located near the unknown points need to be fixed in the leveling loop disconnected area. Further, 3 cm level of accuracy can be achieved if the GNSS survey is performed over two days, for four hours per day. In terms of the geoid model, the latest national geoid model should be applied rather than the EGM08 (Earth Gravitational Model 2008) to minimize regional bias and increase accuracy. Future research is necessary to apply the determination of the GNSS-derived orthometric height technique as a method to connect with the islands because the vertical reference system used inland and that used for the islands in Korea are still different.

Keywords: Leveling Loop Disconnected Area, Leveling Network Adjustment, GNSS-derived Orthometric Height, Adjusted Ellipsoidal Height

1. Introduction

Recently, the determination of the GNSS (Global Navigation Satellite System)-derived orthometric height is attracting attention owing to the development of various satellites and the generalization of GNSS in positioning. Because this technique offers higher cost- and time- efficiency than the spirit leveling, the determination of GNSS-derived orthometric height with a 2–5 cm level of accuracy is being actively studied in Korea, USA and other countries. In 2014, NGII (National Geographic Information Institute) proposed a guideline for the determination of the GNSS-derived orthometric height (NGII, 2014). According to the guideline, an unknown point should be surrounded by more than three known control points. If the target accuracy is 3 cm, GNSS surveying must be performed over two days, for four hours per day. Nevertheless, two hours of GNSS surveying is sufficient if the target accuracy is 5 cm. Further, the adjusted ellipsoidal height calculated by adding the geoidal height from the latest geoid model to the announced orthometric height on the control point should be fixed to compensate for the local bias. Shin *et al.* (2014) determined the orthometric height using the KNGeoid13 (Korean National Geoid 2013) model in eight Korean regions following the guideline and verified the orthometric height compared with the spirit level surveying results. As a result, 91% of the 86 points show less than 3 cm error when the GNSS surveying is conducted for two days, for four hours per day. Further, 96% of the 509

Received 2018. 02. 06, Revised 2018. 02. 21, Accepted 2018. 02. 26

[1] Member, Dept. of Geoinformatics, University of Seoul (E-mail: jsc0704@uos.ac.kr)
[2] Corresponding Author, Member, Dept. of Geoinformatics, University of Seoul (E-mail: jkwon@uos.ac.kr)
[3] Member, Dept. of Geoinformatics, University of Seoul (E-mail: leejs@uos.ac.kr)

data points have less than 5 cm error when two hours of GNSS surveying is applied. According to Lee *et al.* (2017), the KNGeoid14 (Korean National Geoid 2014) model shows the most accurate results compared to the KNGeoid13 and EGM08 (Earth Gravitational Model 2008) models in the determination of the GNSS-derived orthometric height.

However, it is noteworthy that the accuracy assessment in previous studies was performed inland. In other words, a method to determine the orthometric height based on GNSS surveying in an area where the unknown point is not surrounded by more than three control points has not been suggested. As in Korea, the GNSS-derived orthometric height is being determined in Japan by fixing at least three known points near the unknown point. However, for a region in which more than three known points surrounding the unknown point are not available, an exception that allows fixing only two known points is mentioned.

In this study, GNSS surveying and spirit leveling data in the 12th circuit located on the west coast were collected, and the GNSS-derived orthometric heights were calculated considering the arrangement of the control points, observation duration, as well as the geoid model. The accuracy of the GNSS-derived orthometric heights was verified by comparing them with those derived from the leveling network adjustment. Finally, a scheme for the determination of the GNSS-derived orthometric height at the leveling loop disconnected area has been suggested.

2. Methodology

According to the GNSS-derived orthometric height guideline published in 2014, an unknown point should be surrounded by more than three control points to determine the orthometric height based on the GNSS surveying and the local geoid model (Fig. 1). For the control point, the UCP (Unified Control Point) or benchmark that the precise three-dimensional position and orthometric height are known should be used. Further, the distance between the known points should be less than 20 km.

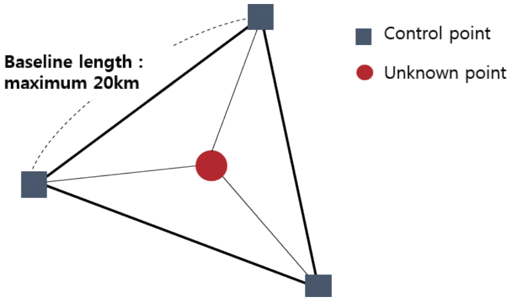

Fig. 1. Arrangement of the control and unknown points

However, the leveling line and loop are not connected in the coastal area and the North Korean border, therefore it is impossible to apply such a triangular arrangement. For example, the roads or bridges are not constructed in the west coast area owing to the irregularity of the coastal lines. Thus, the leveling loop in the 12th circuit located on the west coast is still open (Fig. 2). In the Fig. 2, the white and blue dots mean the currently available 1st and 2nd order benchmarks and the red and blue lines are the spirit leveling lines. The green, pink and yellow lines are the planned sea crossing leveling surveying lines. This means that an unknown point could not be surrounded by the control points except when the control point has been established on the island located on the left side of the coast.

Theoretically, only one control point is required to determine the three-dimensional position by the GNSS relative positioning. However, it is common to apply multiple control points to guarantee the reliability, because of the possibility of change or error in the control points. Unlike the inland area, the change of the terrain is not as large on the coast, therefore the error due to the atmosphere is relatively small. Therefore, it is expected that the determination of the height having high precision is possible without fixing at least three control points.

In this study, the influence of the arrangement of control points was analyzed by comparing the result from fixing one known point with the result of fixing two known points. Because an unknown point could not be surrounded, the geometrical stability is relatively low. Therefore, to confirm whether a longer observation duration is necessary, the ellipsoidal heights have been determined based on the two days, eight hours per day of GNSS surveying and compared with the results from the two days, four hours per day. It is known that the accuracy of the local geoid model is low on the

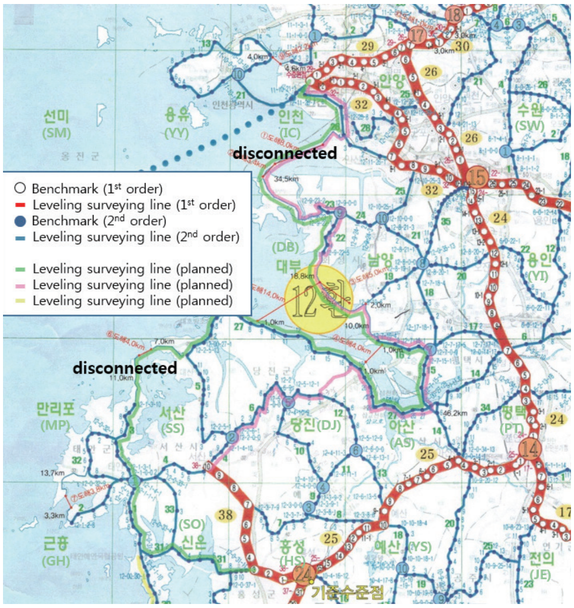

Fig. 2. Distribution of control points (UCPs and benchmarks) and their spirit leveling lines in 12th circuit

leveling loop disconnected area owing to the lower reliability of the orthometric height at the control point. Further, it was reported that the EGM08 model is more suitable at the coast compared to the local geoid models developed before 2014 (Youn, 2014). Therefore, both KNGeoid14 and EGM08 were applied for the GNSS-derived orthometric height determination to find the proper geoid model on the leveling loop disconnected area. The accuracy of the GNSS-derived orthometric height was evaluated by comparing to the result of the leveling network adjustment.

3. Test Area

To verify the accuracy of the GNSS-derived orthometric height, the GNSS and leveling data obtained from the control points and an unknown point are necessary. Further, the orthometric height of the unknown point calculated based on spirit leveling data is required. For the 12th circuit located on the west coast, the disconnection problem of the leveling loop was solved by establishing 10 points of new 2nd order UCPs near the SS (Seosan), NY (Namyang) and DB (Daebu) areas in 2017 by NGII (NGII, 2017). Therefore, the GNSS, leveling data, as well as the reliable orthometric height are available. However, an arrangement surrounding an unknown point with known control points (UCPs or benchmarks) is still impossible. Thus, it is the best target test area to verify the accuracy of the GNSS-derived orthometric height for the leveling loop disconnected area. In this study, two test areas were selected in the 12th circuit. In test area 1, four unknown points (USS04, USS04B, USS13, USS13B) and two control points (U0354, U0356) were available. For reference, USS04B and USS13B are supplementary points established to connect the leveling line by crossing the sea leveling. In test area 2, UDB05, UDB26, and UDB58 were selected as unknown points and U0216 and U0285 were the control points to be fixed.

Fig. 3 shows the distribution of the leveling loop and control points. The red dot and blue dot indicate the 1st order and 2nd order control points, respectively, and the green dot represents the benchmark. The black stars are new 2nd order control points established to connect the leveling loop in the 12th circuit. The sky-blue line is the original leveling surveying line and the purple line is the newly connected one in 2017. Despite adding new surveying lines, the leveling loop could not be closed. Among the original surveying lines, therefore, only the gray lines where the leveling loop could be connected by combining the new surveying lines were applied for the leveling network adjustment.

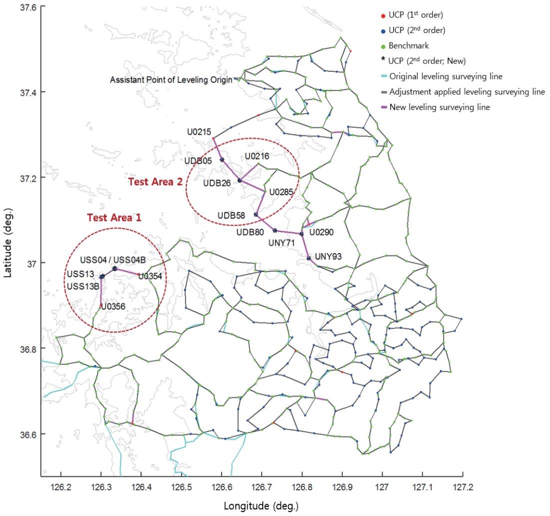

Fig. 3. Distribution test areas

3.1 GNSS surveying

In this study, the GNSS observation data (eight hours per day) obtained from February 23rd, 2017 to February 24th, 2017 were used. To determine the ellipsoidal heights on the unknown points, GNSS surveying was conducted on the unknown points and control points (U0354 and U0356 for test area 1, U0216 and U0285 for test area 2) simultaneously. Following the GNSS-derived orthometric height determination guideline, a dual-frequency receiver was applied and the cut-off angle and data acquisition interval were set to 15° and 30 seconds, respectively.

To check whether the GNSS surveying was well performed, the ellipsoidal heights on the four control points were calculated based on daily observation data spanning eight hours by fixing the INCH, SUWN, DANJ, and SEOS CORS (Continuously Operating Reference Station). In the comparison of the results, it was found that all control points show a difference less than 1 cm. Thus, reliable GNSS surveying data was considered to be obtained. Table 1 shows the difference between the ellipsoidal height of the 1st and 2nd day on each control points.

Table 1. Ellipsoidal height difference of the 1st and 2nd day (unit: cm)

Test Area 1		Test Area 2	
U0354	U0356	U0216	U0285
0.09	0.32	0.05	-0.76

3.2 Leveling surveying

As mentioned before, a total of 10, new 2nd order unified control points were installed to connect the leveling loop in the 12th circuit (Namyang and Seosan regions). Because spirit leveling cannot be performed between USS04 and USS13, two supplement points, USS04B and USS13B, were additionally established on the coast and the sea crossing leveling surveying was performed. The distance between the supplementary points is approximately 3.3 km.

The leveling network adjustment in the 12th circuit was performed by combining the existing leveling line and the new surveying line. In the adjustment, five inconsistent observations were eliminated and the weights of each observation were applied assuming that the observation error increases 2 mm per km. As a result, the orthometric heights were calculated on a total of 619 points, and the estimated height error is less than 2 cm. The result of the leveling network adjustment is summarized in Table 2.

Table 2. Result of leveling network adjustment in the 12th circuit

No. Observation	No. Unknowns	Posterior Variance	Estimate Error at the Unknowns (cm)
687	620	1.22	0.34 – 1.84

4. Accuracy Analysis of GNSS-derived Orthometric Heights

4.1 Arrangement of control points

Since two control points are available in the test area, the GNSS-derived orthometric heights on the unknown points were determined by fixing only one control point of two possible control points and two points simultaneously. Subsequently, the effect of the arrangement and number of fixed control points on the accuracy of the GNSS-derived orthometric height was verified. In the calculation, the final orthometric heights were determined based on the GNSS data obtained for eight hours per day for two days, and the KNGeoid14 was applied to check the influence of the arrangement of control points only.

Fig. 4 and Table 3 indicate the accuracy of the GNSS-derived orthometric heights according to the arrangement of the control points in two test areas. In test area 1, the average absolute error of the unknown points USS04, USS04B, USS13 and USS13B, is calculated to be 2.5 cm when U0354 was fixed. However, an average absolute error of 0.4 cm is obtained when U0356 was the fixed point. This is smaller than the former case, and the accuracy difference is approximately 2 cm. When the two available points are fixed, the average absolute error is 1.26 cm, which is smaller than the result obtained by fixing U0354.

In the previous section, it was confirmed that the difference in ellipsoidal heights of both U0354 and U0356 are less than 1 cm. In addition, when both control points are fixed, the accuracy of the GNSS-derived orthometric height is located somewhere between the results obtained by fixing only one control point.

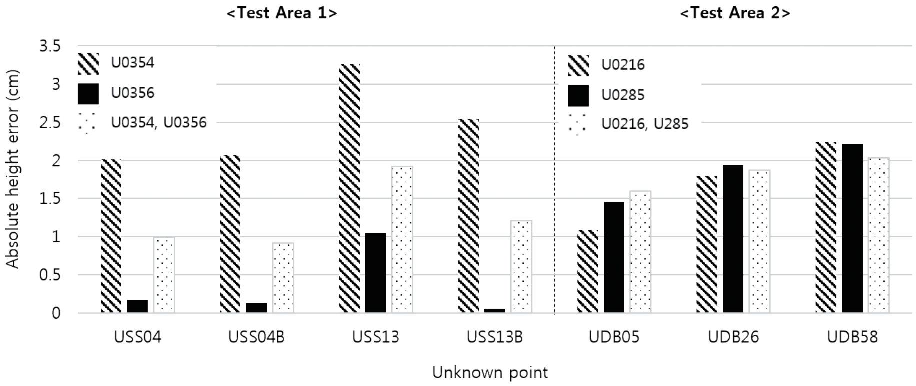

Fig. 4. The accuracy of the GNSS-derived orthometric height in terms of control point arrangement

Table 3. The accuracy of the GNSS-derived orthometric height in terms of control point arrangement (unit: cm)

Test Area 1						Test Area 2				
Unknown point / Fix point	USS04	USS04B	USS13	USS13B	Abs. Mean	Unknown point / Fix point	UDB05	UDB26	UDB58	Abs. Mean
U0354	-2.02	-2.07	-3.27	-2.55	2.48	U0216	1.09	1.8	2.24	1.71
U0356	0.17	0.13	-1.05	0.05	0.35	U0285	1.46	1.94	2.21	1.87
U0354, U0356	-0.99	-0.92	-1.92	-1.21	1.26	U0216, U0285	1.6	1.87	2.03	1.83

Instead of selecting one point, therefore, it is better to fix two available points to guarantee more stable results.

In test area 2, the difference in performance based on the fixed points is small. The error of the GNSS-derived orthometric height is less than 2 cm when U0216 and U0285 are fixed. Among the three unknown points, UDB05 and UDB26 show higher accuracy when U0216 is fixed; UDB58 generates a better result when U0285 is fixed. Therefore, fixing two control points simultaneously is considered a better way to improve the overall stability.

The reliability of the GNSS-derived orthometric height, in particular, could decrease when only one control point is fixed because the error of the fixed point is entirely propagated. Currently, the precision of the orthometric and geoidal height is not provided together; therefore, the reliability of the adjusted ellipsoidal height of each control point could not be evaluated. Therefore, fixing the two available points appears to be a better way to reduce the risk.

4.2 Observation time

According to the GNSS-derived orthometric height determination guideline, observations should be made for four hours per day, for two days, when aiming for 3 cm accuracy. However, those conditions have been suggested with the assumption that the unknown point could be surrounded by three or more control points. Since there are less than three control points available on the leveling loop disconnected area, increasing the observation time would be a way to increase the reliability. In this study, two sets of two day observations, carried out for four hours per day, were generated by mixing data from two day observations of eight hours per day. The GNSS-derived orthometric heights were calculated based on these data sets and compared. To check the independent effect of the observation time on accuracy, two control points that were available for each test area were fixed and the KNGeoid14 was applied.

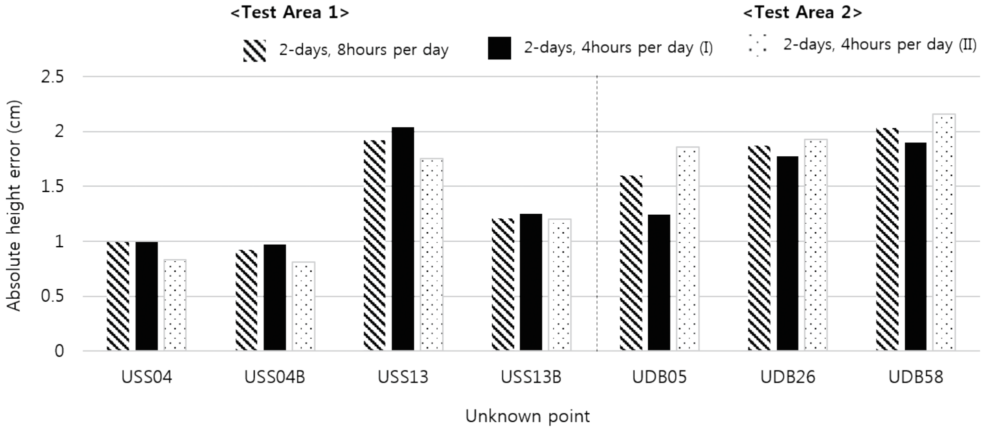

Fig. 5. Accuracy of GNSS-derived orthometric height in terms of observation time

Table 4. Accuracy of GNSS-derived orthometric height in terms of observation time (unit: cm)

Test Area 1						**Test Area 2**				
Unknown point / Observation time	USS04	USS04B	USS13	USS13B	Abs. Mean	Unknown point / Observation time	UDB05	UDB26	UDB58	Abs. Mean
8 hours, 2 days	-0.99	-0.92	-1.92	-1.21	1.26	8 hours, 2 days	1.6	1.87	2.03	1.83
4 hours, 2 days(I)	-0.99	-0.97	-2.04	-1.25	1.31	4 hours, 2 days(I)	1.24	1.77	1.9	1.64
4 hours, 2 days(II)	-0.83	-0.81	-1.75	-1.2	1.15	4 hours, 2 days(II)	1.86	1.93	2.16	1.98

Fig. 5 and Table 4 show the orthometric height error in terms of the observation time. We found that the difference due to the observation time is a few millimeters. The most precise result in test area 1, 1.15 cm, was obtained when data from four hours in the afternoon of the first day and four hours in the morning of the second day were combined. When the observation data were composed of four hours in the morning of the first day and four hours in the afternoon of the second day, a mean absolute error of 1.31 cm was obtained. However, the first combination generates better results, compared to second combination, in test area 2. Nevertheless, the difference in accuracy is still at the millimeter level. Even though the same observation time combination is applied, one optimal observation time combination could not be specified. In particular, the difference between a two day observation for eight hours per day and a two day observation for four hours per day was shown to be at the millimeter level. Therefore, it is concluded that observations can be performed for four hours per day for two days.

4.3 Geoid model

The latest geoid model, the KNGeoid14, was constructed by fitting the local gravimetric geoid based on the EGM08 and various gravity data, to 1,080 points of the GNSS/Leveling data on the UCPs and CORSs. Although the overall fitting precision of the KNGeoid14 was 3.3 cm, the precision generally decreased for mountainous areas. However, certain points with more than 3 cm error were detected in the test area, which is a relatively smooth region (Fig. 6).

Baek *et al.* (2013) reported that the overall precision of the EGM08 is 6 cm and Youn (2014) found that the EGM08 is more suitable than the geoid models developed before 2012 for coastal regions. Thus, the reliability of both the EGM08 and KNGeoid14 were verified and an attempt was made to identify the geoid model that is more appropriate for the leveling loop disconnected area. To verify the effect of the geoid model, the GNSS-derived orthometric height was calculated based on the data for two days, recorded for eight hours per day, and the two available control points were fixed together.

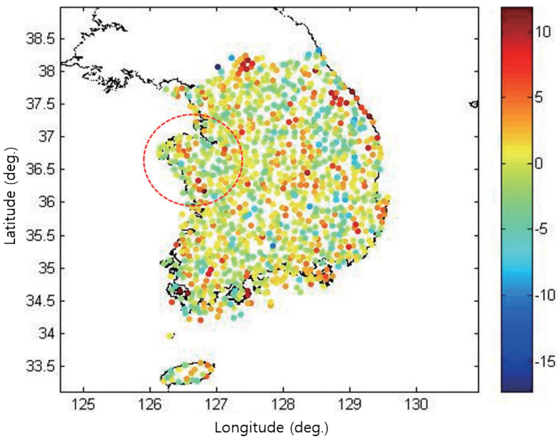

Fig. 6. Precision of KNGeoid14 (unit: cm)

The effect of the geoid model on the accuracy of the GNSS-derived orthometric heights is summarized in Fig. 7 and Table 5. In test area 1, both the KNGeoid14 and EGM08 generated errors less than 2 cm. In test area 2, the KNGeoid14 could determine the GNSS-derived orthometric height with a maximum error of 2.03 cm, which is less than the standard (3 cm). However, the maximum error was 3.84 cm when the EGM08 was used. Unlike UDB05 and UDB26, which show positive differences, UDB58 shows a negative difference such that the local consistency is lower for the EGM08. Therefore, the latest national hybrid geoid model should be applied as specified in the GNSS-derived orthometric height guideline.

5. Summary and Conclusion

In this study, the accuracy of the GNSS-derived orthometric height has been analyzed in terms of the arrangement of control points, observation time, and geoid models in two regions located on 12th circuit. From the test results, the method to determine the GNSS-derived orthometric height on the leveling loop disconnected area is suggested as follows:

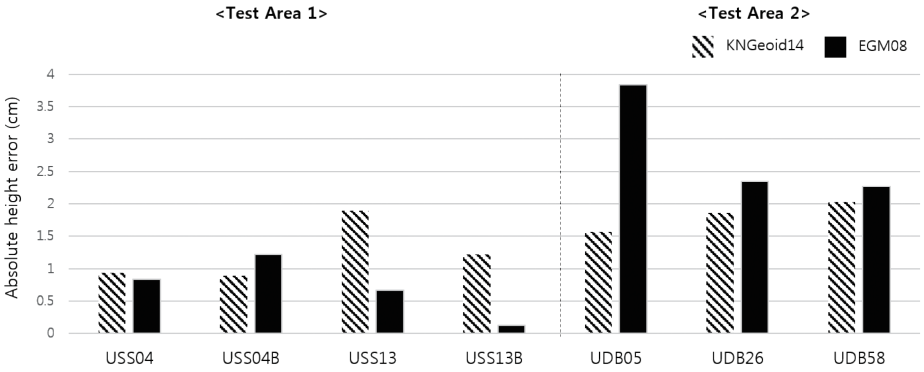

Fig. 7. Accuracy of GNSS-derived orthometric height in terms of geoid model

Table 5. Accuracy of GNSS-derived orthometric height in terms of geoid model (unit: cm)

Test Area 1						Test Area 2				
Unknown point Geoid model	USS04	USS04B	USS13	USS13B	Abs. Mean	Unknown point Geoid model	UDB05	UDB26	UDB58	Abs. Mean
KNGeoid14	-0.94	-0.9	-1.9	-1.22	1.24	KNGeoid14	1.57	1.86	2.03	1.82
EGM08	0.84	1.22	-0.67	-0.13	0.72	EGM08	3.84	2.35	-2.27	2.82

It is impossible to surround an unknown point with three or more control points on the leveling loop disconnected area following the existing GNSS-derived orthometric height determination guideline. In this study, the accuracy of the GNSS-derived orthometric height was determined by fixing only one point and two points simultaneously, and the effect of the arrangement of control points was compared. As a result, it was confirmed that the overall error is smaller when only one point is applied selectively than when two points are fixed together. However, the selection of the fixed point results in a maximum difference of up to 2 cm. Further, the error on the announced orthometric height of the control point and the local geoid model completely propagates to the GNSS-derived orthometric height when only one point is selected. Therefore, it is preferable to use two points to guarantee the stability at the medium level.

The GNSS-derived orthometric height determined using the observations over two days, for eight hours per day and the observations over two days, for four hours per day, and the effect of the observation time was evaluated. Despite the different observation times, all unknown points show less than 2 cm of error and their difference is not as large as several millimeters. Therefore, it was concluded that the GNSS-derived orthometric height with a 3 cm level of accuracy could be calculated even if the GNSS surveying is conducted over two days, for four hours per day.

To check the reliability of KNGeoid14 and to identify a suitable model at the coast, both KNGeoid14 and EGM08 were applied to determine the GNSS-orthometric height. All unknown points show less than 3 cm error when KNGeoid14 is applied. Otherwise, the maximum error reaches up to 3.84 cm when the EGM08 model is applied. Therefore, the latest local geoid model should be applied for determining the orthometric height based on the GNSS surveying.

Although the leveling loop is not closed, the leveling surveying could be applied near the coastal area. This means that the orthometric height connected to the origin of the vertical datum could be determined even if the reliability is relatively low. However, it is impossible to perform the spirit leveling to connect the height between the inland and islands. Therefore, the vertical reference system is separated. Owing to the same reason, it is known that the geoid model error is up to 1 m. In particular, the distance between the control points and an unknown point is typically more than 20 km. Therefore, a follow-up study is necessary to identify the proper method to apply the GNSS-derived orthometric height as a way of connecting the vertical datum between the inland and island.

Acknowledgment

This research was supported a grant from geospatial information workforce development program funded by the Ministry of Land, Infrastructure and Transport of Korean Government (2016-04-03).

References

Baek, K.M., Kwon, J.H., and Lee, J. (2013), Precision verification of new global gravitational model using GPS/leveling data, *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography,* Vol. 31, No. 3, pp. 239-247. (in Korean with English abstract)

Lee, S.B., Lee, K.S., and Lee, M.K. (2017), Analysis of the feasibility of GNSS/geoid technology in determining orthometric height in mountain, *Journal of the Korean Society for Geospatial Information Science*, Vol. 25, No. 2, pp. 57-65. (in Korean with English abstract)

NGII (2014), *GNSS-derived Orthometric Heights Guideline (Ver.1.0)*, NGII, Suwon, Korea, pp. 2-7.

NGII (2017), *The Improved Scheme for the Vertical Reference System based on the Unified Control Points (Part 2. The Detailed Surveying Manual considering Surveying Environments to Determine the Optimal Height)*, Publication No.11-1613436-000136-01, NGII, Suwon, Korea, pp. 47-100.

Shin, G.S., Han, J.H., and Kwon, J.H. (2014), Accuracy analysis of orthometric heights based on GNSS static surveying, *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography*, Vol. 32, No. 5, pp. 527-537. (in Korean with English abstract)

Youn, J.H. (2014), *An Analysis of a Geoid Model for Determining the Vertical Datum of Island Areas using GNSS/leveling*, Master's thesis, Kyonggi University, Gyeonggi-do, Korea, 53p.