Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography
Vol. 38, No. 2, 153-163, 2020
https://doi.org/10.7848/ksgpc.2020.38.2.153

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

Precision Evaluation of Recent Global Geopotential Models based on GNSS/Leveling Data on Unified Control Points

Lee, Jisun[1) · Kwon, Jay Hyoun[2)

Abstract

After launching the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) which obtains high-frequency gravity signal using a gravity gradiometer, many research institutes are concentrating on the development of GGM (Global Geopotential Model) based on GOCE data and evaluating its precision. The precision of some GGMs was also evaluated in Korea. However, some studies dealt with GGMs constructed based on initial GOCE data or others applied a part of GNSS (Global Navigation Satellite System) / Leveling data on UCPs (Unified Control Points) for the precision evaluation. Now, GGMs which have a higher degree than EGM2008 (Earth Gravitational Model 2008) are available and UCPs were fully established at the end of 2019. Thus, EIGEN-6C4 (European Improved Gravity Field of the Earth by New techniques – 6C4), GECO (GOCE and EGM2008 Combined model), XGM2016 (Experimental Gravity Field Model 2016), SGG-UGM-1, XGM2019e_2159 were collected with EGM2008, and their precisions were assessed based on the GNSS/Leveling data on UCPs. Among GGMs, it was found that XGM2019e_2159 showed the minimum difference compared to a total of 5,313 points of GNSS/Leveling data. It is about a 1.5cm and 0.6cm level of improvement compare to EGM2008 and EIGEN-6C4. Especially, the local biases in the northern part of Gyeonggi-do, Jeju island shown in the EGM2008 was removed, so that both mean and standard deviation of the difference of XGM2019e_2159 to the GNSS/Leveling are homogeneous regardless of region (mountainous or plain area). NGA (National Geospatial-Intelligence Agency) is currently in progress in developing EGM2020 and XGM2019e_2159 is the experimentally published model of EGM2020. Therefore, it is expected that the improved GGM will be available shortly so that it is necessary to verify the precision of new GGMs consistently.

Keywords: Global Geopotential Model, Earth Gravitational Model 2008, Experimental Gravity Field Model 2019e_2159, GNSS/Leveling data, Precision Evaluation

1. Introduction

GGM (Global Geopotential Model) which describes the Earth's gravity field using satellite, ground, and altimetry data, is essential for local geoid modeling as well as height unification of various countries. It is broadly used in the field of geophysics, oceanography and military; hence, the selection of suitable GGM for the target area is important. Since the development of the first GGM, SE 1 (Standard Earth 1) in 1966, around 180 GGMs have been modeled and published till date using various satellites and ground gravity data (ICGEM, 2020a; Lundquist and Veis, 1966). The most popular one, EGM08 (Earth Gravitational Model 2008), developed by NGA (National Geospatial-Intelligence Agency) in 2008, has been used for local geoid modeling and the conversion of ellipsoidal to orthometric height in Korea (Bae *et al*., 2012; Lee *et al*., 2012; Lee and Kim, 2012; NGII, 2018). However, it was modeled based on CHAMP

Received 2020. 04. 07, Revised 2020. 04. 24, Accepted 2020. 04. 28

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

(CHAllenging Minisatellite Payload) and GRACE (Gravity Recovery and Climate Experiment), developed in the early 2000s (Pavlis *et al*., 2008). In other words, it didn't include data from the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) , which obtains high-resolution gravity signals based on the gravity gradiometer. Since 2010, many research institutes have focused on developing new geopotential models that include GOCE data, with the number of GGMs reaching up to sixty (ICGEM, 2020a). Hence, the precision of the new GGMs is must be evaluated.

In general, the precision of GGM has been evaluated using GNSS (Global Navigation Satellite System)/Leveling data located in the target area, so that such data achieved on UCPs (Unified Control Points) have been applied for assessment in Korea (Baek *et al*., 2013; Kim *et al*., 2020; NGII, 2018; NGII, 2019). Previous studies used a part of the UCPs with irregular distribution as their installation was complete by year-end 2019. Consequently, it is appropriate to evaluate the precision of GGMs based on fully-installed GNSS/Leveling data with high-resolution and regularity. It is expected that such high-resolution of GNSS/Leveling data will contribute to evaluating the precision objectively in mountainous areas. Here, newly developed GGMs including GOCE and local ground gravity data were obtained and their precision was evaluated based on GNSS/Leveling data on UCPs to find the most suitable GGM in Korea.

2. Global Geopotential Model

2.1 Definition

In geodesy, the mathematical function that describes the Earth's gravity field in the three-dimensional space is called GGM (Barthelmes, 2014). Various institutes such as NGA, ESA (European Space Agency) and GFZ (GeoForschungsZentrum Potsdam) combine gravity signals from satellites, altimetry and local surveying and model the gravity field by spherical harmonic analysis. Thus, GGMs are usually divided into satellite-only and combined models. The satellite-only models are computed from satellite measurements alone whereas combined models make additional use of terrestrial gravity measurements over the continents and mean sea surface surfaces from altimetry over the oceans. The gravity signals from satellites are quite smooth as their orbits cannot be lower than a few hundreds of kilometers (Barthelmes, 2014); therefore, special resolution of the satellite-only models is lower than that of combined ones.

A set of spherical harmonic coefficients is provided while developing a new GGM. Thus, users download the coefficients file and compute gravity information (i.e., gravity anomaly, geoidal height) at the point P with the target resolution at a certain point by summing up the degree and order of a spherical harmonic expansion, using Eqs. (1) and (2). For more details regarding GGMs, please refer to Barthelmes (2014), Heiskanen and Moritz (1967) and Jekeli (1999).

$$\Delta\mathrm{g} = \frac{GM}{R^2}\sum_{n=2}^{N_{max}}(n-1)\sum_{m=0}^{n}(\overline{C_{nm}}\,cosm\lambda_P + \overline{S_{nm}}\,sinm\lambda_P)\,\overline{P_{nm}}\,\sin\varphi_P \quad (1)$$

$$\mathrm{N} = \mathrm{R}\sum_{n=2}^{N_{max}}\sum_{m=0}^{n}(\overline{C_{nm}}\,cosm\lambda_P + \overline{S_{nm}}\,sinm\lambda_P)\,\overline{P_{nm}}\,\sin\varphi_P \quad (2)$$

where GM is a product of gravitational constant and mass of the Earth, R is reference radius, n and m are the maximum degree and order, $\overline{C_{nm}}$ and $\overline{S_{nm}}$ are normalized spherical harmonic coefficients, $\overline{P_{nm}}$ is Legendre function, φ_P and λ_P are the latitude and longitude of the point P.

2.2 Models

Since the development of the first GGM, SE1, around 180 GGMs are currently available. The spherical harmonic coefficients of all GGMs are collected by the ICGEM (International Center for Global Earth Models) so that it is possible to download by accessing the website http://icgem.gfz-potsdam.de/ICGEM/. (Barthelmes and Köhler, 2013; Lundquist and Veis, 1966; ICGEM, 2020a).

Among GGMs, EGM96 (Earth Gravitational Model 1996), EIGEN-CG03C (European Improved Gravity Field of the Earth by New techniques – CG03C) and EGM2008 which have been used for local geoid modeling are well-known in Korea (Förste *et al*., 2005; Lemoine *et al*., 1998; Pavlis *et al*., 2008). Especially, EGM2008 is broadly used worldwide. However, it should be mentioned that those GGMs were developed based on CHAMP and GRACE launched in the early 2000s. A new satellite called GOCE was launched in 2009, and the gravity gradiometer was equipped to obtain high-resolution gravity field information. In other words, a GGMS with high spatial resolution can be developed with observations from GOCE which is sensitive to the shorter wavelengths of the gravity field owing to the gravity gradiometer (Bouman and Fuchs, 2012; ESA, 2020); however, previous models such as EGM2008 did not include the new gravity signal from GOCE. New GGMs based on GOCE gravity signals are being currently developed. Following the first development of GGM that used initial GOCE data in 2010, approximately sixty GGMs were developed until the end of 2019 (ICGEM, 2020). Many studies have also focused on analyzing the precision of new models to confirm the effect and improvement by including GOCE data (Abd-Elmotaal, 2015; Godah and Krynski, 2013; Grombein *et al*., 2017; Tocho *et al*., 2014; Vergos *et al*., 2014).

The precision of GGMs was evaluated in previous studies. However, Baek *et al*. (2013) dealt with the GGMs (i.e. GOCO03S (Gravity Observation Combination 03S), EIGEN-6C) developed that initially included GOCE data. NGII(2018), NGII(2019) and Kim *et al*.(2020) collected newer models such as GECO (GOCE and EGM2008 Combined model), XGM2016 (Experimental Gravity Field Model 2016), however, the distribution of GNSS/Leveling data used for the comparison with was irregular; this is because that the installation of the new control point called UCP was complete by year-end 2019. About 40 new GGMs have been published since 2014, and improved precision of recent GGMs is expected because they have been developed by combining EGM2008 with GOCE gravity signal. Many studies report that the newly developed GGMs based on the GOCE data show better precision than EGM2008; therefore, it is necessary to evaluate the precision of new models even for local geoid development (Förste *et al*., 2014; Gilardoni *et al*., 2016; Liang *et al*., 2018). Consequently, the precision of EGM2008, EIGEN-6C4, XGM2016, GECO, SGG-UGM-1 and XGM2019e_2159 was assessed based on fully installed UCPs. Important details such as development year, agency and basic data of each GGM was summarized below (Table 1).

The most popular model, EGM2008, was developed by NGA. The maximum degree of EGM2008 is 2,190. NGA combined GRACE-based GGM, ITG-GRACE03S, with local ground gravity data, ArcGP (Arctic Gravity Project), and both SIO (Scripps Institution of Oceanography) / NOAA (The US National Oceanic and Atmospheric Administration) and DNSC07 (Danish National Space Center 2007) altimeter data. The gravity signal estimated based on the DTM2006.0 (Digital Terrain Model, 2006) topography data was filled in the region where the spatial resolution of other gravity data was lower than 5km. The precision of EGM2008 was estimated to be about 13cm on comparison with 12,387 points of GNSS/Leveling data distributed worldwide (Pavlis *et al*., 2008; Pavlis *et al*., 2012).

EIGEN-6C4 with the maximum degree of 2,190 was modeled by GFZ in 2014. GOCE data obtained from November 2009 to October 2013 were combined with LAGEOS (LAser Geodynamics Satellite) and GRACE at the low frequencies, and the DTU10 (Danish Technical University 2010) altimeter and EGM2008 were combined for the higher frequency of gravity signal modeling. Förste *et al*.(2014) reported that the precision of EIGEN-6C4 was improved by 1~2mm compared to EGM2008 based on a set of GNSS/Leveling data located in Europe, USA(United States of America) and Australia.

In 2015, Polytechnic University of Milan developed GECO up to a maximum degree of 2,190. As GOCE data contributes to precision improvement at the low and middle frequencies, Polytechnic University of Milan combined EGM2008 with the newly developed GOCE-based GGM (GOCE-TIM-5R) for the high-frequency gravity signal. GECO showed about 16.3cm of RMS (Root Mean Square) difference compared to EIGEN-6C developed in 2011, otherwise, 12.8cm for EGM2008 (Gilardoni *et al*., 2016).

XGM2016 was developed by TUM (Technical University of Munchen) and NGA in 2016 as an initial version of EGM2020. In the modeling, GOCO05C which included the GOCE gravity signal, ground and GRAV-D (Gravity for the Redefinition of the Vertical Datum) airborne gravity data was in charge of the lower and middle-frequency parts, and recent ground data offered by NGA, was added to model the high-frequency signals. As XGM2016 was modeled while developing EGM2020, the maximum degree was limited to 719; it is relatively lower than others such as EGM2008, EIGEN-6C4 and GECO, etc. In comparison with EGM2008 and EIGEN-6C4, the maximum difference of geoidal height in the ocean area is about 2m; however it reaches up to 5.7m and 4.2m respectively in South America (Pail *et al*., 2018).

Wuhan University in China developed SGG-UGM-1 by combining GOCE gravity signal obtained during November 2009 - May 2012 with EGM2008 in 2018, with maximum degree of 2,159. When verifying precision based on available GNSS/Leveling data, the precision of EGM2008 improved slightly from 28.4cm to 28cm in North America, while in China, EGM2008 showed a precision of about 24cm, but the precision of SGG-UGM-1 improved to 16.2cm (Liang *et al*., 2018).

The most recent GGM, XGM2019e_2159, is the follow-up version of XGM2017 and almost before EGM2020. In the development of XGM2019e_2159, the satellite-only GGM called GOCO06S was combined with ground and altimetry data which were applied for modeling XGM2016. Gruber *et al*. (2019) reported that XGM2019e_2159 showed better precision than EGM2008 owing to the GOCE and new ground gravity data and the estimated accuracy of the model is 1~10cm according to the topography. The description of each models have been commented at the NGII(2018) and NGII(2019).

3. Precision Evaluation

In general, there are two representative surveying techniques to determine height. GNSS supports determining an ellipsoidal height which is vertical to the reference ellipsoid; otherwise, the orthometric height which is perpendicular to the mean sea level is determined by spirit leveling and gravity surveying or leveling with gravity compensation. Because those two heights refer to different vertical reference surfaces, the difference in the direction called DOV (Deflection Of Vertical) exists. However, the magnitude of DOV is relatively small, especially in local surveying, so it is negligible (Fig. 1 and Eq. (3)). Thus, the difference between the ellipsoidal height and orthometric height would be approximated to be the geoidal height.

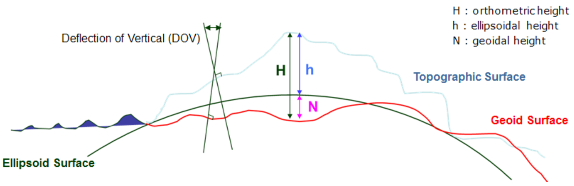


Fig. 1. Relationship of heights

$$N_{GNSS/Leveling} = \mathrm{h} - \mathrm{H} \tag{3}$$

where $N_{GNSS/Leveling}$ is a geometric geoidal height based on ellipsoidal height(h) and orthometric height(H)

Table 1. Characteristics of GGMs

Geopotential Model	Year	Agency	Nmax	Fundamental Data
EGM2008	2008	NGA	2,190	S(ITG-GRACE03S), A, G,
EIGEN-6C4	2014	GFZ	2,190	S(GOCE, RACE, LAGEOS), A, G
GECO	2015	Polytechnic Univ. of Milan	2,190	S(GOCE), EGM2008
XGM2016	2017	Munchen Technical Univ. NGA	719	S(GOCO05C), A, G
SGG-UGM-1	2018	Wuhan Univ.	2,159	S(GOCE), EGM2008
XGM2019e_2159	2019	Polytechnic Univ. of Milan	760 2,190 5,540	S(GOCO06S), A, G

S : Satellite or satellite-based GGM, A : Altimeter, G : Ground

Geometrically determined geoidal height based on the GNSS and leveling surveying data in the test region is broadly used to evaluate the precision of GGMs. For reference, the orthometric height of leveling data refers to the local mean sea level; otherwise, the globally determined mean sea level is applied for the GGM. It means that there is a bias between the geoidal height from the local GNSS/Leveling data and that from a GGM as large as the difference of mean sea level. Consequently, the local precision of the GGM was commonly evaluated as a standard deviation without the mean.

3.1 Based on global GNSS/Leveling data

As mentioned before, ICGEM collects and offers a set of spherical harmonic coefficients. It collects global GNSS/Leveling data located in Europe, Australia, Japan, USA, and Canada, and provides the evaluated precision of GGMs (ICGEM, 2020b); thus the precision improvement of GGMs could be checked. When assuming the maximum degree, the precision of selected GGMs in this study based on a total of 12,036 points of GNSS/Leveling data would be found in Table 2. Except for the XGM2016 which has a lower maximum degree compared to the others, the difference in precision does not exceed 5mm. EGM2008 had an overall precision of about 24cm while EIGEN-6C4, GECO, SGG-UGM-1 and XGM2019_2159 which included GOCE data, showed 3~5mm level of improvement. On comparing XGM2016 and XGM2019e_2159, the overall precision was improved from 24.89cm to 23.61cm. This is due to an update of the fundamental dataset as well as the spatial resolution difference resulting from an increase in the maximum degree. In particular, an improvement level of around 3.5cm was observed in Japan. However, it should be mentioned that these evaluations were conducted using foreign countries' GNSS/Leveling data only. As precision improvement was found in Japan on the application of XGM2019_2159, the better precision is also expected in Korea but may be inconclusive. Consequently, GNSS/Leveling data located in Korea should be collected and applied to verify the local precision of GGMs.

3.2 Based on GNSS/Leveling data on UCPs

3.2.1 GNSS/Leveling data on UCPs

As mentioned, the precision of GGMs was evaluated by Beak *et al.*(2013) and NGII(2018, 2019). However, Baek *et al.* (2013) used 1,032 points of first order UCP established between 2008 and 2010 and tested GGMs (GOCO02S, GOCO03S, EIGEN-6D4 and EIGEN-6C2) developed before 2014. Kim *et al.* (2020) verified the precision of the EIGEN-6C4 and GECO but the used GNSS/Leveling data has been limited to 1,182 points of UCPs. In the research project funded by NGII (National Geographic Information Institute), the precision of recent models such as GECO and XGM2016 were verified; however, a total of 4,616 points, a part of currently available UCPs installed until the end of 2017, was applied (NGII, 2018; NGII 2019). In other words, previous studies only applied a part of the GNSS/Leveling data because the installation of whole UCPs wrapped up at the end of 2019. Consequently, the previous dataset shows an irregular distribution and the density is non-homogeneous over Korea. Especially, majority of the previous dataset is from Chungchoeng-do and Jeolla-do, where the variation in

Table 2. Precision of GGMs (ICGEM, 2020b) (unit: cm)

Geopotential Model	Nmax	Australia	Brazil	Canada	Europe	Japan	USA	Total
Number of GNSS/Leveling data		**201**	**1,112**	**2,691**	**1,047**	**816**	**6,169**	**12,036**
EGM2008	2,190	21.7	46.0	12.8	12.5	8.3	24.8	23.97
EIGEN-6C4	2,190	21.2	44.6	12.6	12.1	7.9	24.7	23.61
GECO	2,190	21.6	45.1	13.1	12.3	8.0	24.6	23.71
XGM2016	719	21.8	44.0	15.1	14.0	12.5	26.3	24.89
SGG-UGM-1	2,159	21.7	44.6	13.0	12.1	7.6	24.5	23.53
XGM2019e_2159	2,190	21.5	43.8	12.8	12.7	9.0	24.8	23.61

topography is relatively smooth, as shown in Fig. 2.

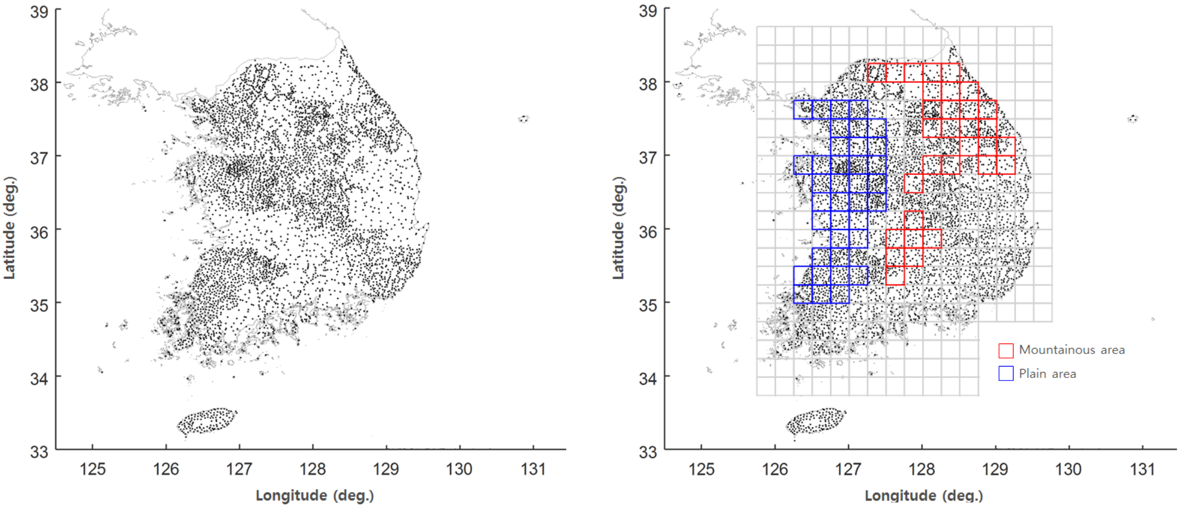
A total of 5,313 UCPs were collected and applied to evaluate the precision of recent GGMs. For reference, 5,622 UCPs were established over Korea; however, some UCPs did not have ellipsoidal or orthometric height due to a request of movement, construction, etc. Some researchers also pointed out the relatively lower reliability of the official heights of UCPs as network adjustment of the GNSS and spirit leveling were not carried out. Therefore, GNSS/Leveling data on UCPs were compared to the newly developed local geoid model, KNGeoid18, and a part of the UCPs which show smaller than 10cm of difference were only extracted for the test.

Baek *et al.*(2013) subdivided the first order UCPs into mountainous area (Kangwon-do) and plain areas (Chungcheong-do and Jeolla-do); however, the boundaries of those areas were limited empirically. In this study, data for both mountainous and plain area were extracted but the average heights based on the topography were applied as a standard to determine the test area to guarantee objectivity. NGII divides Korea into 0.25' x 0.25' cells for the map generation so that it is possible to compute the average of topography of each cell. Thus, the mountainous area was selected where an average topographical height is over 400m, especially near Jiri mountain and Kangwon-do, while plain area had an average of 10~200m in the south-western part of Korea. A coastal area with an average height of 10~200m could refer to different reference surface so that latitude for the plain area were limited over 35°.

Fig. 2 shows the distribution of GNSS/Leveling data on UCPs; the left one shows 4,616 points used in the NGII research, while the right one shows those points applied in this study. The new dataset showed homogeneous distribution over Korea. Also, the red box in the right figure indicates the mountainous area, while the blue indicates the plain area. A total of 787 and 1,319 points of GNSS/Leveling data are located in the mountainous and plain areas, respectively.

3.2.2 Precision Assessment

The difference in GNSS/Leveling data between UCPs and GGMs is summarized in Table 3 when the maximum degree was applied. The difference of geoidal height was calculated as geoidal height from GGM minus geometric one from GNSS/Leveling data. Among GGMs, it was found that XGM2019e_2159 showed the minimum difference, that of 5.65cm of standard deviation. It is an improvement of around 1.5cm compared to EGM2008 which showed 7.11cm of standard deviation, and 2.7cm for XGM2016. XGM2019e_2159 also has the minimum standard deviation in the case of the plain area. The difference in standard



(a) 2017

(b) 2019

Fig. 2. Distribution of UCPs

deviation between each GGM is only 4mm when GECO and XGM2016 which show inconsistent results were eliminated, so that the differences in GGMs were not notable. On the other hand, EIGEN-6C4 showed the minimum standard deviation in the mountainous area; it showed an improvement of only 3~4mm over XGM2019e_2159 and 1cm over EGM2008. However, the most suitable GGM should be selected when overall standard deviation is minimum. Especially, the difference of standard deviation between EIGEN-6C4 and XGM2019e_2159 in mountainous area is smaller than the difference of overall precision so that it can be concluded that XGM2019e_2159 is the most suitable GGM. Also, it should be emphasized that the combined GOCE gravity signal had positive effects on precision improvement. Unfortunately, GECO shows the maximum standard deviation overall, including the plain as well as the mountainous area, despite a high maximum degree compared to XGM2016. As the precision remains at around 10cm in the plain area, it is not a suitable model in Korea.

As shown in Table 3, the most precise GGM in Korea is XGM2019e_2159. However, EGM2008 is being broadly applied. Therefore, XGM2019e_2159 and EGM2008 were directly compared to check the effect of GOCE and newly updated ground data for GGM modeling. Fig. 3 shows the difference between GNSS/Leveling and GGMs (EGM2008 and XGM2019e_2159), which is quite notable. The figure on the right, demonstrating the difference between GNSS/Leveling data and XGM2019e_2159, shows a homogeneous trend. This means that there is no remarkable difference per region. However, the difference between GNSS/Leveling data and EGM2008 shows inconsistent regional characteristics. Regionally, the northern part of Gyeonggi-do (near the border of North Korea), south-eastern part (Gyeongsangnam-do) and Jeju-do showed relatively large local difference. Especially, the northern part of Gyeonggi-do shows a local difference larger than -10cm. In the analysis, it was mentioned that the precision of EGM2008 was poorer than that of XGM2019e_2159 in the mountainous area, which is one of the reason, as the northern part of Gyeonggi-do has been included within the mountainous area. Also, regional inconsistency appeared because average difference between GNSS/Leveling data and EGM2008 in the mountainous

Table 3. Precision of GGMs in Korea (unit: cm)

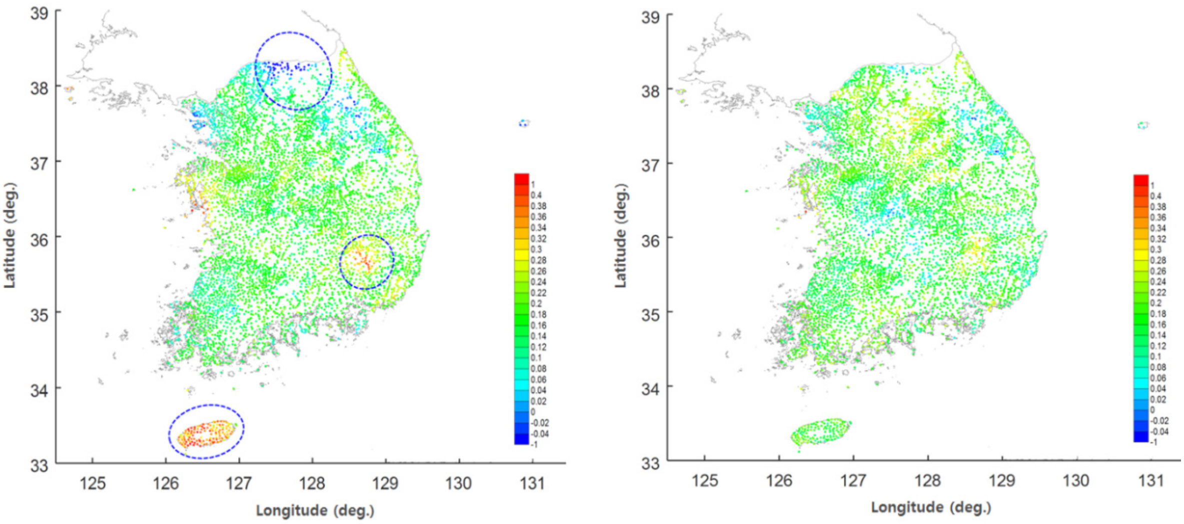
Geopotential Model	Nmax	Region	Min	Max	Mean	STD
EGM2008	2,190	Whole	-16.02	48.49	17.15	7.11
		Mountain	-15.16	33.49	11.99	7.37
		Plain	-4.02	39.58	17.02	5.56
EIGEN-6C4	2,190	Whole	-7.08	39.72	17.75	6.26
		Mountain	-6.10	36.14	16.25	6.34
		Plain	-5.53	33.25	15.15	5.53
GECO	2,190	Whole	-13.83	44.58	18.59	9.12
		Mountain	-13.59	40.84	13.25	8.79
		Plain	-13.83	41.07	16.50	10.41
XGM2016	719	Whole	-42.53	44.92	17.86	8.32
		Mountain	-19.70	44.84	15.74	10.32
		Plain	-9.43	33.58	16.28	6.33
SGG-UGM-1	2,159	Whole	-9.90	43.59	17.57	6.27
		Mountain	-9.90	33.14	14.26	6.37
		Plain	-4.13	35.05	17.17	5.97
XGM2019e_2159	2,190	Whole	-10.00	40.69	17.38	5.65
		Mountain	-10.00	34.12	15.54	6.70
		Plain	-1.33	31.14	16.22	5.10

areas was 11.99cm, while that of the plain area was 17cm. For reference, XGM2019e_2159 showed a difference of 15.54cm and there is no large difference of regional average. Thus, it could be mentioned that there is a local bias in EGM2008. In addition, it is notable that such a large difference in Jeju-do was also removed in XGM2016e_2159.

These characteristics could be found on showing the difference between EGM2008 and XGM2019e_2159. As mentioned before, XGM2019e_2159 is a newly developed GGM that includes GOCE data as well as ground gravity data. Thus, the difference in GGMs was calculated at the maximum degrees of 280 and 2190. The reason to select 280 was to check the satellite effect, otherwise, a maximum degree(2190) was applied to check the high frequency of ground data. Fig. 4 shows the difference between the GGMs. As shown in Fig. 4, the difference between GGMs mainly appears in the northern part of Gyeonggi-do, south-eastern region and Jeju-do. An overall trend of differences was found when the maximum degree applied was 280, and the magnitude of those differences was around 10cm. In other words, XGM2019e_2159 generated homogeneous difference over the whole test area compared to GNSS/Leveling data because regional biases were removed. In the case of Gyeongsangnam-do, the main region to make a difference could be assumed to be ground data. On applying maximum degree, relatively detailed changes appeared in the region, which led to the removal of relatively large local differences.

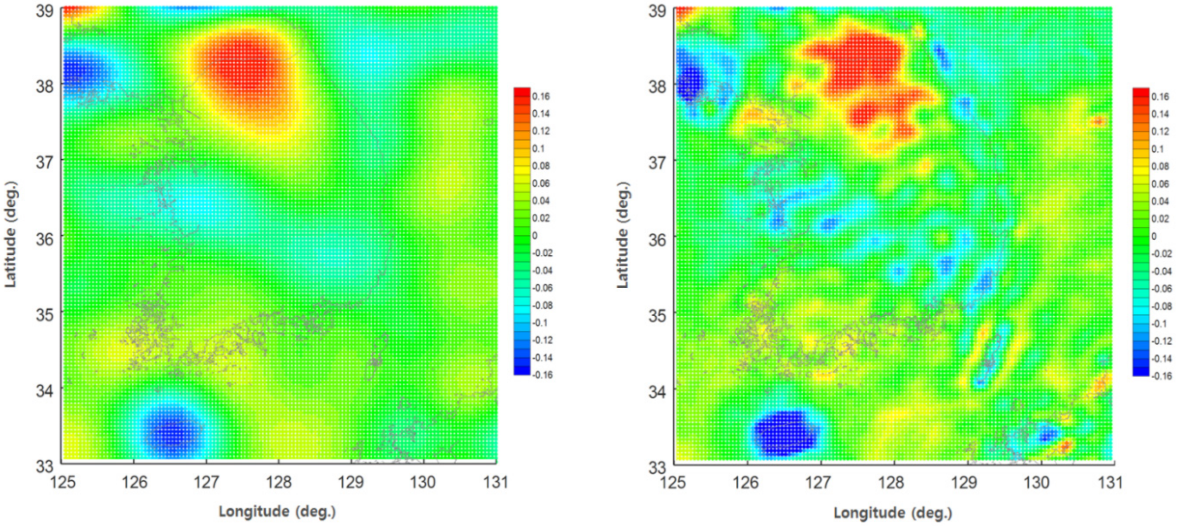
Thus, it can be concluded that combining GOCE with updated ground data has a positive effect in improving precision of a GGM. Some regional biases have been removed and the new model represents local characteristics for detail. The precision of newly developed GGMs is being continuously improved by including GOCE and ground gravity data; hence it is necessary to collect and analyze new models to find the most suitable one in Korea.

For reference, XGM2016 which showed the minimum standard deviation compared to around 4,000 points of GNSS/Leveling data was applied to develop the KNGeoid18. Applying a degree of 719 and comparing with 5,313 points of GNSS/Leveling data, the precision of XGM2016 and XGM2019e_2159 was calculated to be 8.32cm and 8.26cm, respectively (NGII, 2019). The difference is quite small but it is being updated. XGM2019e_2159 is almost final test version of EGM2020 so that the precision of EGM2020 is expected to be improved in Korea. Thus, the use of EGM2020 will be widen, especially in updating the local geoid model as well as a vertical reference surface connection.



(a) EGM2008 **(b) XGM2019e_2159**

Fig. 3. Geoidal height difference between GGM and GNSS/Leveling data in Korea



(a) Nmax = 280 **(b) Nmax = 2190**

Fig. 4. Geoidal height difference between EGM2008 and XGM2019e_2159 in Korea

4. Conclusion

In this study, EGM2008 and new GGMs (EIGEN-6C4, GECO, XGM2016, SGG-UGM-1, and XGM2019e_2159) developed by including GOCE and ground gravity data were collected. Their precision was evaluated based on a total of 5,313 points of GNSS/Leveling data obtained on UCPs.

Among the six different GGMs, XGM2019e_2159, the most recently developed one, was found to be the most precise. The overall precision in Korea was calculated to be 5.65cm, an improvement of around 1cm as compared to EGM2008 which is generally used in many studies. EGM2008 showed inconsistent precision in the mountainous and plain areas, and the average difference between GNSS/Leveling data and EGM2008 was 11.99cm and 17.02cm, respectively. Unlike regional bias in EGM2008, XGM2019e_2159 showed homogeneous precision over Korea, and both average and standard deviation of the difference between GNSS/Leveling and XGM2019e_2159 are quite similar. The reason for these positive effects was confirmed by the fact that the GOCE gravity signal and newly updated ground data were included in the recent GGM modeling. Especially, a large update was found in the northern part of Gyeonggi-do, Gyeongsangnam-do and Jeju-do and the standard deviation in those regions decreased in XGM2019e_2159 as compare to EGM2008.

After launching GOCE, many research institutes have focused on developing new GGMs including gravity data from GOCE. Their efforts have led to improving precision of GGMs. Therefore, it is necessary to monitor, collect the new GGMs steadily and find the most suitable GGM in Korea to update the local geoid model and unify the height reference system. As a previous version of EGM2020, XGM2019e_2159 showed improved precision as compared to EGM2008, additional improvement of EGM2020 is also expected.

References

Abd-Elmotaal, H.A. (2015), Validation of GOCE models in Africa, *Newton's Bull*, Vol. 5, pp. 149-162.

Bae, T.S., Lee, J., Kwon, J.H., and Hong, C.K. (2012), Update of the precision geoid determination in Korea, *Geophysical prospecting*, Vol. 60, No. 3, pp. 555-571.

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)

Barthelmes, F. (2014), Global Models, *Encyclopedia of Geodesy*, Springer International Publishing, Cham, Switzerland.

Barthelmes, F. and Köhler, W. (2013), ICGEM–status of the IAG service for global Earth gravity field models after the first decade, *The IAG Scientific Assembly 2013, 150th Anniversary of the IAG (Potsdam 2013)*, 1-6 September, Potsdam, Germany.

Bouman, J. and Fuchs, M.J. (2012), GOCE gravity gradients versus global gravity field models, *Geophysical Journal International*, Vol. 189, No. 2, pp. 846-850.

ESA (2020), *ESA EO Missions (GOCE)*, https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/goce (last date accessed: 05 April 2020).

Förste, C., Flechtner, F., Schmidt, R., Meyer, U., Stubenvoll, R., Barthelmes, F., König, R., Neumayer, K.H., Rothacher, M., Reigber, C., Biancale, R., Bruinsma, S.L., Lemoine, J.M., and Raimondo, J.C. (2005), A new high resolution global gravity field model derived from combination of GRACE and CHAMP mission and altimetry/gravimetry surface gravity data, *EGU General Assembly 2005*, 24-29 April, Vienna, Austria.

Förste, C., Bruinsma, S., Abrikosov, O., Flechtner, F., Marty, J.C., Lemoine, J.M., Dahle, C., Neumayer, H., Barthelmes, F., Konig, R., and Biancale, R. (2014), EIGEN-6C4-The latest combined global gravity field model including GOCE data up to degree and order 1949 of GFZ Potsdam and GRGS Toulouse, *EGU General Assembly 2014*, 27 April – 2 May, Vienna, Austria.

Gilardoni, M., Reguzzoni, M., and Sampietro, D. (2016), GECO: a global gravity model by locally combining GOCE data and EGM2008, *Studia Geophysica et Geodaetica*, Vol. 60, No. 2, pp. 228-247.

Godah, W. and Krynski, J. (2013), Evaluation of recent GOCE geopotential models over the area of Poland, *Acta Geodyn Geomater*, Vol. 10, No. 3, pp. 379-386.

Grombein, T., Seitz, K., and Heck, B. (2017), On high-frequency topography-implied gravity signals for a height system unification using GOCE-based global geopotential models, *Surveys in geophysics*, Vol. 38, No. 2, pp. 443-477.

Gruber, T., Zingerle, P.H. Pail, R., and Oikonomidou X. (2019), High resolution gravity field models as global reference surface for heights, *SIRGAS 2019*, 11-14 November, Rio de Janeiro, Brazil.

Heiskanen, W. A. and Moritz, H. (1967), *Physical Geodesy*, W.H. Freeman and Co, San Francisco, CA, USA.

ICGEM (2020a), *Global Gravity Field Models, ICGEM(International Centre for Global Earth Models)*, http://icgem.gfz-potsdam.de/tom_longtime (last date accessed: 06 April 2020).

ICGEM (2020b), *RMS about Mean of GPS/Leveling Minus Gravity Field Model Derived Geoid Heights*, http://icgem.gfz-potsdam.de/tom_gpslev (last date accessed: 06 April 2020).

Jekeli, C. (1999), An analysis of vertical deflections derived from high-degree spherical harmonic models, *Journal of Geodesy*, Vol. 73, No. 1, pp. 10-22

Kim, K.B., Yun, H.S., and Choi, H.J. (2020), Accuracy evaluation of geoid heights in the national control points of south Korea using high-degree geopotential model, *Applied Sciences*, Vol. 10, No. 4, pp. 1466-1476.

Lee, J., Kwon, J.H., Baek, K.M., and Moon, J. (2012), Development of Korean geoid model and verification of its precision, *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography*, Vol. 30, No.5, pp. 493-500. (in Korean with English abstract)

Lee, S.B. and Kim, C.Y. (2012), Development of regional gravimetric geoid model and comparison with EGM2008 gravity-field model over Korea, *Scientific Research and Essays*, Vo. 7, No. 3, pp. 387-397.

Lemoine, F.G., Kenyon, S.C., Factor, J.K., Trimmer, R.G., Pavlis, N.K., Chinn, D.S., Cox, C.M., Klosko, S.M., Luthcke, S.B., Torrence, M.H., Wang, Y.M., Williamson, R.G., Pavlis, E.C., Rapp, R.H., and Olson, T.R. (1998), *The Development of the Joint NASA GSFC and the National IMagery and Mapping Agency (NIMA) Geopotential Model EGM96*, NASA/TP-1998-206861, GSFC Goddard Space Flight Center, Greenbelt, Maryland, USA.

Liang, W., Xu, X., Li, J., and Zhu, G. (2018), The determination of an ultra-high gravity field model SGG-UGM-1 by combining EGM2008 gravity anomaly and GOCE observation data, *Acta Geodaetica et Cartographica*

Sinica, Vol. 47, No. 4, pp. 425-434.

Lundquist, C.A. and Veis, G. (1966), *Geodetic Parameters for a 1966 Smithsonian Institution standard Earth*, SAO special report, Smithsonian Institution, Astrophysical Observatory, pp. 6-104.

NGII (2018), *2017 Development of Geoid and Vertical Datum Transformation Model* (Part 1), Final Research Report, Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, Suwon, Korea, pp. 12-18.

NGII (2019), *Establishment of Mid to Long-term Strategy for National Reference Frame in Korea (Part 1)*, Final Research Report, Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, Suwon, Korea, pp. 109-113.

Pail, R., Fecher, T., Barnes, D., Factor, J.F., Holmes, S.A., Gruber, T., and Zingerle, P. (2018), Short note: the experimental geopotential model XGM2016, *Journal of Geodesy*, Vol. 92, pp. 443-451.

Pavlis, N.K., Holmes, S.A., Kenyon, S.C., and Factor, J.K. (2008), An earth gravitational model to degree 2160 : EGM2008, *EGU General Assembly 2008*, 13-18 April, Vienna, Austria.

Pavlis, N. K., Holmes, S. A., Kenyon, S. C., and Factor, J. K. (2012), The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), *Journal of geophysical research: solid earth*, Vol. 117, B04406, pp. 1-38.

Tocho, C., Vergos, G.S., and Pacino, M.C. (2014), Evaluation of GOCE/GRACE Derived Global Geopotential Models over Argentina with Collocated GPS/Levelling Observations, In: Marti (ed.), *Gravity, Geoid and Height Systems (Proceedings of the IAG Symposium GGHS2012), Springer, Cham*, pp. 75-83.

Vergos, G.S., Grigoriadis, V.N., Tziavos, I.N., and Kotsakis, C. (2014), Evaluation of GOCE/GRACE Global Geopotential Models over Greece with collocated GPS/Levelling observations and local gravity data, In: Marti (ed.), *Gravity, Geoid and Height Systems (Proceedings of the IAG Symposium GGHS2012), Springer, Cham*, pp. 85-92.