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Full Length Research Paper

Development of regional gravimetric geoid model and comparison with EGM2008 gravity-field model over Korea

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We constructed a regional geoid model and compared it with the EGM2008 global gravity-field model to evaluate the performance of EGM2008 for Korea. By using the Remove–Compute–Restore (RCR) technique, we developed an improved gravimetric geoid model JNUGEOID2010 on a 1 × 1′ grid by combining the EIGEN-GL04C global geopotential model (GGM), 8316 land-gravity data, an altimetry-derived marine gravity model DNSC08, and the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM). The computations were done using a two-dimensional four-band spherical fast Fourier transform (FFT) with 100% zero padding. In addition, we compared the Korean national gravimetric geoid model KGEOID98 to EGM2008. For the comparison, geometric geoid heights derived from 735 GPS-levelling stations were used. The smallest standard deviation of geoid height differences is ± 0.163 m for EGM2008 to degree and order 2190. Thus, we conclude that the new model EGM2008 is superior to the two regional gravimetric geoid models, JNUGEOID2010 and KGEOID98, for Korea.

Key words: Regional geoid model, EGM2008, Global geopotential models, GPS-levelling, geoid height, Korea.

INTRODUCTION

Because of the development of space geodesy techniques such as GPS, the range of application of geometric geoids is increasing in various fields. The development of precise geoid models to determine the orthometric height by using GPS technology is an active field that is in progress, especially in the field of geodetic surveying.

Several studies exist that deal with the development of a geoid model for Korea (Lee, 1996, 2000; Lee et al., 1996; Yun, 1999). The first Korean national geoid model KGEOID98 was released publicly in 1998 by the Korean National Geodetic Information Institute (NGII). However, the accuracy of these studies and this national geoid model, whose standard deviation is approximately 30 cm, is unsatisfactory, so a more precise geoid model is desired. The main objective of this study is therefore to develop an improved regional geoid model for Korea. So, a Korean gravimetric geoid model JNUGEOID2010 is developed based on the reference surface of the EIGEN-GL04C global geopotential model (GGM) with gravity data and digital elevation modelling (DEM) using the Remove–Compute–Restore (RCR) technique. Previously, evaluation of five GGMs was done to find the most suitable GGM and four-band spherical fast Fourier transform (FFT) and residual-terrain model (RTM) terrain reduction methods were used for determining the middle- and short-frequency part of the gravimetric geoid, respectively, in the RCR technique.

Another objective of this study was to evaluate the performance of the ultra-high-resolution gravity-field model EGM2008, which was published by the National Geospatial Intelligence Agency (NGA) in 2008 (Pavlis et al., 2008) while this study was in progress. Since then, several evaluations of this model have shown that it represents a significant achievement and improves the

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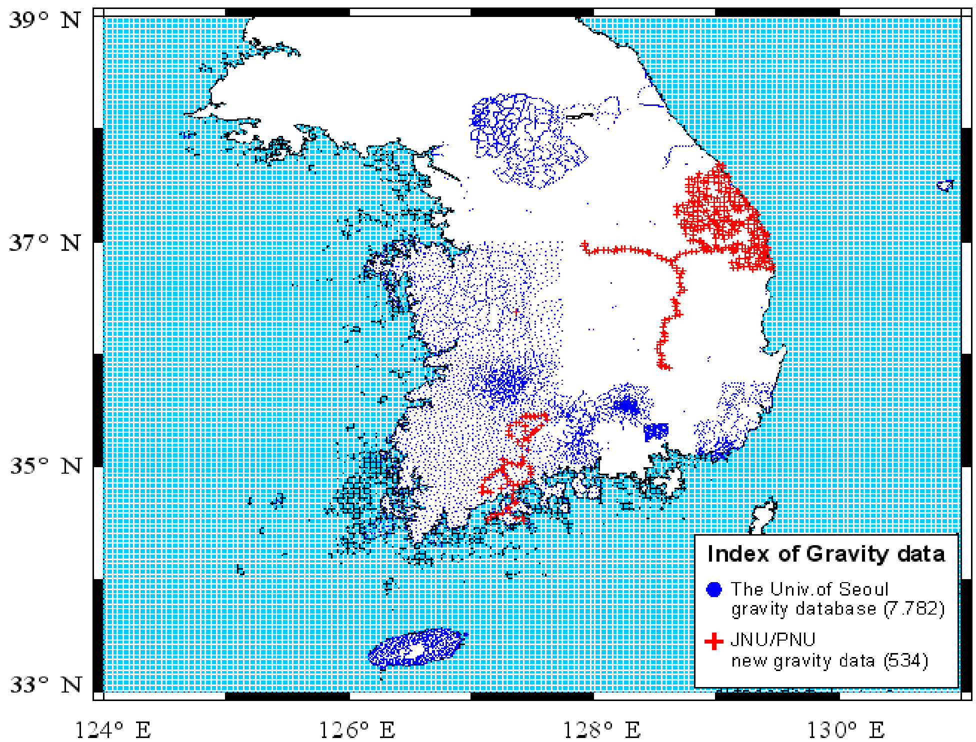

Figure 1. Distribution of 8316 land gravity data and DNSC altimetry data in Korea.

resolution of the global gravity field (Dawod et al., 2010; Kuroishi, 2009; Yilmaz et al., 2010). However, an evaluation of EGM2008 in the context of a precise Korean geoid model is still lacking.

The accuracy of the geoid models is strongly dependent on the quality and quantity of the gravity data that enter the solution. However, the computation of gravimetric geoid models in developing countries suffers mainly from sparse and inaccurate terrestrial gravity observations (Kiamehr, 2006). Korea has same problem regarding the density and accuracy of the terrestrial gravity data. In some very sparse areas, there are areas which exceed the spatial resolution of the EGM2008 in void regions of the surface gravity data, such as the upper part and right part, in Korea, as you can see in Figure 1.

To this end, we compare a Korean national geoid model and the new gravimetric geoid model JNUGEOID2010 with EGM2008. To perform this comparison, we use geometric geoid heights computed from 735 GPS-levelling stations to find the best way to perform geoid determination in Korea.

MATERIALS

Gravity data

For this study, we used the University of Seoul gravity database (Lee et al., 2008; Hong et al., 2009), which contains 7782 land-gravity data and 534 new-gravity data acquired by Pusan National University (PNU) and Jinju National University (JNU) in 2009. This database was constructed by collecting all available gravity data for 2008 from the Korean Institute of Geoscience and Mineral Resources and the PNU and reprocessing it in a consistent manner using outlier detection. The accuracy of the gravity data is 0.488 *mGal* after cross-over adjustment. For marine areas, we used 105,445 gravity-anomaly data extracted from grid points of the DNSC08 mean sea-surface model (Anderson et al., 2009). Figure 1 shows the distribution of the land-gravity data and the DNSC08 sea-gravity grid-point data. Unfortunately, irregular data distribution caused by void regions of the surface gravity data is inevitable. Gravity data were distributed at 1 point per 12 km^2 on average but there are some areas which exceed the spatial resolution of the EGM2008 in void regions of the surface gravity data such as the upper part and right part, except for some areas in Korea.

GPS-levelling data

We used two GPS-levelling data sets over Korea to compute geometric geoid heights. The first data set was provided by the Hanjin Information Systems and Telecommunications Co. Ltd (HIST) and consists of 455 GPS ellipsoidal height data at benchmarks. For this study, we verified the quality of the GPS-levelling data before comparing it with the geoid height of the Earth geopotential model. In Figure 2, the HIST data are denoted by purple triangles and a JNU-GPS campaign was planned to increase the data in sparse areas during 2009 to 2010. Like the JNU-GPS campaign, GPS surveying on the national Korean first- and second-order levelling network was performed by JNU. From this effort, a second data set was constructed consisting of 280 GPS ellipsoidal height data at benchmarks containing 197 GPS levelling data from the Gyungbuk-2009 network and 83 GPS levelling data from the Chonnam-2010 network, and Figure 2 shows the data distribution

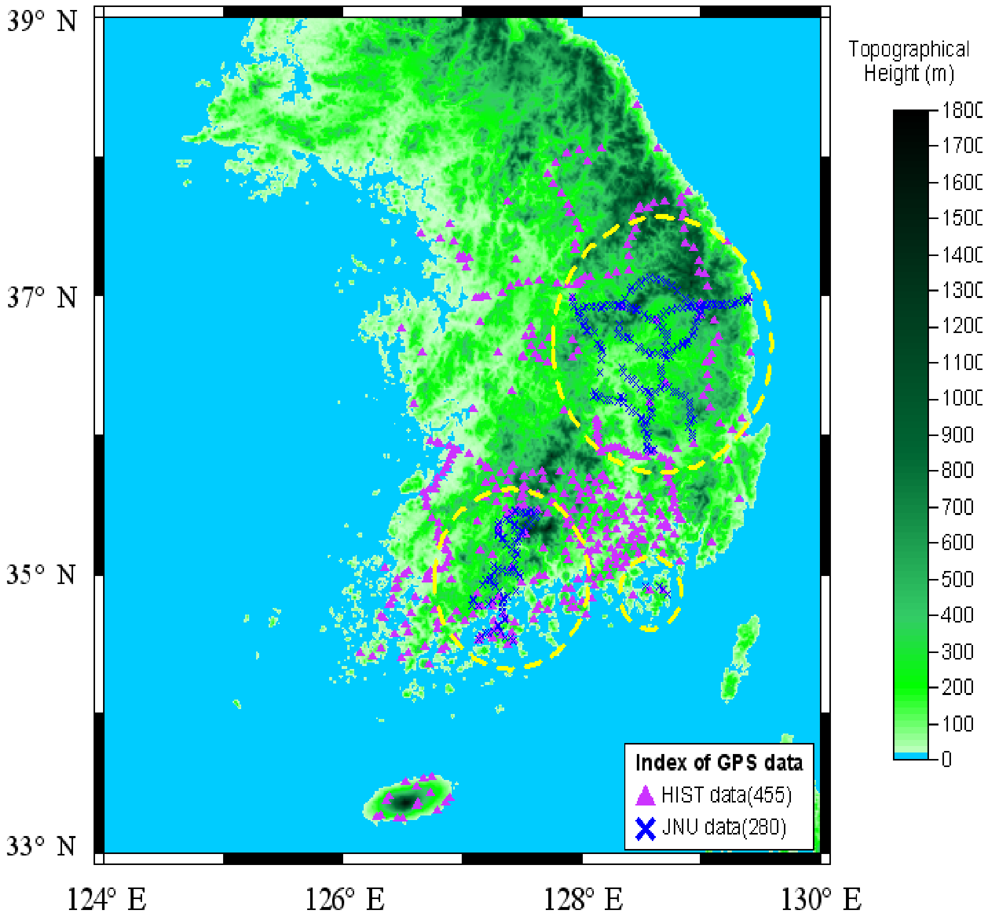

Figure 2. The topography and distribution of 735 GPS-levelling data in Korea.

Table 1. Description of the GPS work on the levelling network by the JNU-GPS campaign.

Description	Gyungbuk-2009	Chonnam-2010
Number of GPS-levelling BMs	197	83
Number of outliers removed	3	2
GPS receiver type	dual frequency	dual frequency
Number of sessions and duration	25 and 1 h	11 and 1 h
Coordinates datum	ITRF2000	ITRF2000
Local geodetic datum	KGD2002	KGD2002

of this second data set with blue crosses. The outliers in the GP-levelling data were detected by considering geoid height differences at the benchmarks and were eliminated. The orthometric height information of the benchmarks was supplied by the NGII. Table 1 summarizes the local GPS work done by the JNU-GPS campaign and Table 2 shows the statistics of the GPS-levelling-derived geoid.

The geometric geoid heights were computed from these 735 GPS-levelling data (that is, the sum of the first and second data sets) using Equation (1) (Heiskanen and Moritz, 1967) after removing the discrepancies between the two data sets:

$$N = h - H \qquad (1)$$

Where N is the geoid height, h is the ellipsoidal height computed from GPS, and H is the orthometric height. The geoid heights were used to evaluate the accuracy of the GGMs and gravimetric geoid models.

KGEOID98

KGEOID98, released publicly in 1998, is the first Korean national geoid model, so we compare the EGM2008 gravity-field model to the KGEOID98 regional geoid model to evaluate the accuracy of the former. KGEOID98 is a gravimetric geoid model developed by

Table 2. Statistics of the GPS-levelling-derived geoid from the data of the JNU-GPS campaign (m).

Campaign	Number of data	Min.	Max.	Mean	Std dev.
Gyungbuk-2009	197	26.180	29.553	28.305	0.821
Chonnam-2010	83	25.973	27.652	26.729	0.429

Table 3. Global geopotential models used in this study.

Model	Year	Max. degree	Data*	Reference
EIGEN-GL04C	2006	360	S (GRACE, LAGEOS), G, A	Förste et al. (2006)
GGM02C	2004	200	S (GRACE), G, A	Tapely et al. (2005)
PGM2000A	2000	360	S, G, A	Pavlis et al. (2000)
EGM96	1996	360	S (EGM96), G, A	Lemoine et al. (1998)
OSU91A	1991	360	S (GEMT2), G, A	Rapp et al. (1991)
EGM2008	2008	2190	S (Grace), G, A	Pavlis et al. (2008)

* Data: S = satellite tracking data, G = gravity data, A = altimetry data.

the RCR technique that involves applying a two-dimensional multiband spherical FFT followed by a restoration of the terrain effects based on OUS91A GGM by using the same methodology and nearly the same data, except the GPS-levelling data, as for KGEOID96 (Lee, 1996). Data were gridded over the area 32 to 43° N by 123 to 132° E with a basic grid spacing of 5 × 5′ (Choi et al., 1998).

Global geopotential models

EIGEN-GL04C is a gravity-field combination model with coefficients determined by GeoForschungsZentrum Potsdam (GFZ) and the Groupe de Recherche de Géodésie Spatiale, Toulouse, from the GRACE and LAGEOS missions with 0.5 × 0.5° gravimetry and altimetry surface data and spherical harmonic coefficients to degree and order 360. The accuracy of this model at its full spatial resolution is estimated to be 15 cm (Förste et al., 2006; Förste et al., 2008).

GGM02C, a higher resolution global gravity model, combined GGM02S with terrestrial gravity information (surface gravity and mean sea surface) using the TEG4 covariance. The GGM02S gravity model was estimated with 363 days of GRACE K-band range-rate, attitude, and accelerometer data. The GGM02S field was estimated to degree and order 120 and the GGM02C solution was created to degree and order 200 (Tapely et al., 2005).

PGM2000A, an improved geopotential model, was presented at the TOPEX/JASON Science working team meeting in 2000 (Pavlis et al., 2000). PGM2000A was an EGM96 derivative model that incorporates normal equations for the dynamic ocean topography implied by the POCM4B ocean circulation model. PGM2000A maintains the orbit and land geoid modelling performance of EGM96 while improving its marine geoid modelling capability.

EGM96 is a spherical harmonic model of the Earth's gravity potential to degree 360 (Lemoine et al., 1998). This model allows one to compute geoid undulations to better than one-metre accuracy and realizes WGS84 as a true three-dimensional reference system**.**

The OSU91A model contains harmonics up to degree and order 360 and was a previous model of EGM96. The OSU91A model was developed through the combination of the GEMT2 coefficients set, GEOS3/SEASAT altimeter-derived anomalies, and the terrestrial gravity data base at Ohio State University (Rapp et al., 1991).

EGM2008

EGM2008 was publicly released by NGA in 2008. This gravitational model is complete to spherical harmonic degree and order 2160, with some additional coefficients up to degree and order 2190 that offer a spatial resolution of 9 km. EGM2008 incorporates improved 5 × 5′ gravity anomalies and altimetry-derived gravity anomalies and has benefited from the latest GRACE-based satellite solutions (Pavlis et al., 2008). This model represents the state-of-the-art of global high resolution modelling.

METHODS

Geoid undulation performance of global geopotential models over Korea

Currently, various GGMs with great accuracy exist because improved methods have been developed to acquire new gravity and altimetry data. The geoid can be determined regionally from precise and regionally detailed information concerning the gravity field with reference to a relevant GGM. The accuracy of such a regional geoid model at long wavelengths is governed by the accuracy of the GGM (Kuroishi, 2009). Therefore, in the first approach, we evaluate the accuracy of five suitable GGMs for Korea: the EIGEN-GL04C, GGM02C, PGM2000A, EGM96, and OSU91A models, as compiled in Table 3. We treated EGM2008 as an independent geoid model in this practice because it has high resolution and high accuracy.

In spherical approximation the gravity anomaly Δg_{GGM} and the geoid height N_{GGM} are represented using a set of spherical harmonic coefficients by the following equations (Heiskanen and Moritz, 1967):

$$\Delta g_{GGM} = \frac{GM}{R^2}\sum_{\ell=2}^{L}(\ell-1)\sum_{m=0}^{\ell}(\bar{C}_{\ell m}\cos m\lambda + \bar{S}_{\ell m}\sin m\lambda)\times \bar{P}_{\ell m}(\sin\varphi) \quad (2)$$

Table 4. Statistics of geoid heights computed from five GGMs (m).

Model (Nmax)	Min.	Max.	Mean
EIGEN-GL04C (360)	15.087	33.204	25.034
GGM02C (200)	15.484	33.332	25.038
PGM2000A (360)	15.397	33.228	25.042
EGM96 (360)	15.406	33.303	25.062
OSU91A (360)	15.417	32.653	24.955

Table 5. Statistics of geoid heights differences $(N_{Model} - N_{GPS/Leveling})$ of five GGMs (m).

Model (Nmax)	Min.	Max.	Mean	Std dev.
EIGEN-GL04C (360)	–0.904	0.784	–0.107	0.188
GGM02C (200)	–1.202	0.759	–0.156	0.309
PGM2000A (360)	–0.851	0.927	–0.148	0.230
EGM96 (360)	–0.889	0.927	–0.185	0.246
OSU91A (360)	–1.137	1.018	–0.305	0.262

$$N_{GGM} = R\sum_{\ell=2}^{L}\sum_{m=0}^{\ell}\overline{P_{\ell m}}(\sin\varphi)(\overline{C}_{\ell m}\cos m\lambda + \overline{S}_{\ell m}\sin m\lambda) \quad (3)$$

Where GM is the geocentric gravitational constant referring to the total earth mass, R is the mean radius of the earth, and $\overline{P}_{\ell m}$ are the fully normalised associated Legendre functions, given degree ℓ and order m. $\overline{C}_{\ell m}$ and $\overline{S}_{\ell m}$ are the fully normalised harmonic coefficients of the disturbing potential and φ and λ are the geodetic latitude and longitude, respectively. The finite series is usually truncated at the maximum degree of the expansion ℓ = L. The fully normalised spherical harmonic coefficients ($\overline{C}_{\ell m}$ and $\overline{S}_{\ell m}$) supplied for each of these geopotential models are used in Equations 2 and 3, together with the defining parameters of GRS80, to compute gravity anomaly and geoid heights, respectively. At a higher degree, a GGM's accuracy is quite dependent on the geographic coverage of the gravity data that go into the solution (Ellmann and Jürgenson, 2008).

For the evaluation, we compared the geoid heights from every GGM with the geometric geoid heights derived from the 735 GPS-levelling data. First, we performed spherical harmonic synthesis for the area of Korea from 33 to 39° N and from 124 to 131° E, applying the maximum degree and order according to each GGM, and we calculated the geoid heights of the GGM with the defining parameters of GRS80 using a total of 151,200 points at a basic grid spacing of 1′ in latitude and longitude.

Table 4 shows the statistics of geoid height distributions computed from five geopotential models and Table 5 shows the difference between the geoid heights of each GGM and those derived from GPS levelling. As a result of analysing the accuracy according to every GGM as in Table 5, the standard deviation of the EIGEN-GL04C model which applies up to degree and order 360 is ±0.188 m, and this model presented greater accuracy relative to the other four models. The GGM02C model which applies up to degree and order 200 presented the worst accuracy among the five GGMs, because the standard deviation of the model was found to have the largest value: ±0.309 m. Figure 3 shows the distribution of geoid heights of the EIGEN-GL04C model, which showed the best accuracy.

Regional gravimetric geoid modelling and evaluation

In the second approach, an improved regional gravity-field model for Korea was constructed by combining terrestrial gravity data and an altimetry-derived marine gravity model DNSC08 with EIGEN-GL04C using the RCR technique. The concept of geoid determination by the RCR technique implies that both topography and low-degree gravity signals are removed before computation and restored after Stokes' integration (Sjöberg, 2005). The geoid or quasigeoid is estimated using Stokes' and Molodensky's formulae with gravity anomalies, Δg as input data. Before applying Stokes' formula, the gravity anomaly must be reduced using the remove step of the RCR technique (Omang et al., 2000; Erol et al., 2009):

$$\Delta g = \Delta g_{FA} + \Delta g_{GGM} + \Delta g_{Terr-eff} \quad (4)$$

Where Δg_{FA} is the free-air anomaly, given as a point value at the surface of the topography. Δg_{GGM} is the reference gravity anomaly given by Equation (2), and $\Delta g_{Terr-eff}$ is the terrain effect. The terrain effect, consisting of the Bouguer plate, terrain correction, and the indirect effect, is the volume integral of a disturbing mass anomaly (Forsberg, 1984).

The gravimetric geoid is obtained after applying the restore step and the geoid height can be computed by the following equation (Omang et al., 2000; Erol et al., 2009):

$$N_{Grav} = N_{GGM} + N_{\Delta g} + N_{Terr-eff} \quad (5)$$

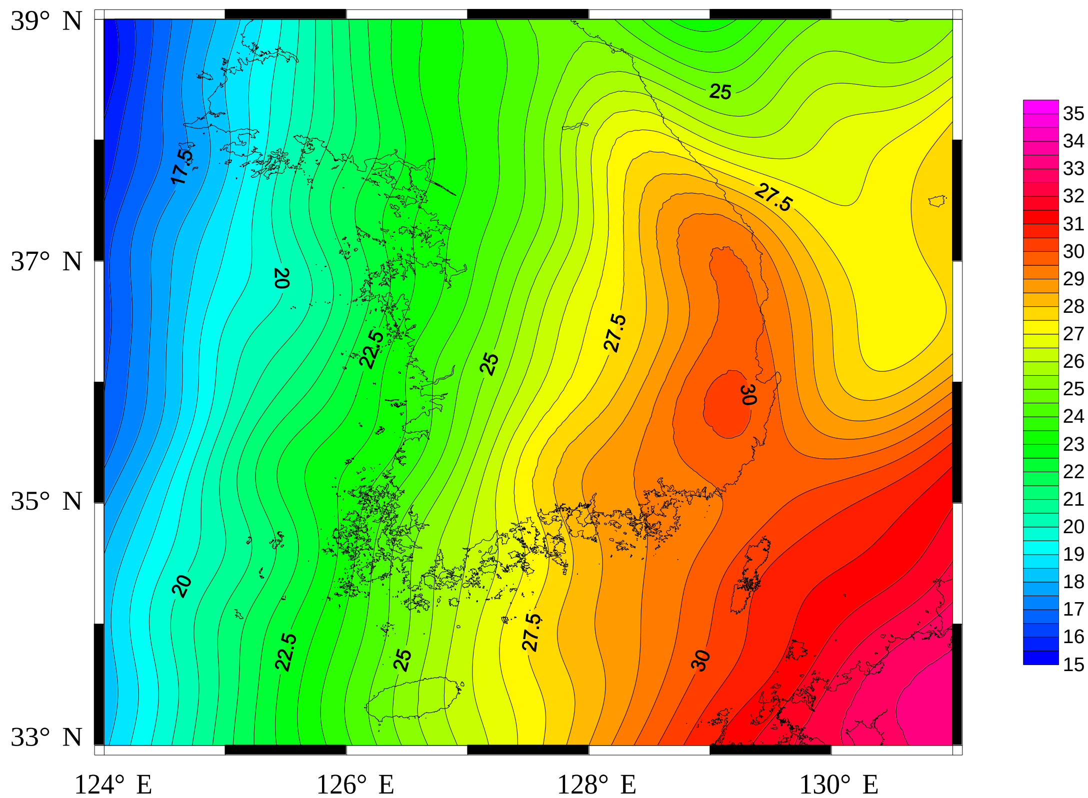

Figure 3. Geoid heights of EIGEN-GL04C model over Korea.

Where N_{GGM} is the low-frequency part of the geoid obtained from the GGM by Equation (3). For computation of the reference geoid height N_{GGM}, we used the EIGEN-GL04C model, which is the most accurate among the five GGMs.

The medium-frequency part $N_{\Delta g}$ of the geoid is the residual geoid computed from residual anomalies using Stokes' integration. The residual geoid height is computed from Stokes' equation (Heiskanen and Moritz, 1967):

$$N_{\Delta g} = \frac{R}{4\pi\gamma}\iint_{\sigma} \Delta g S(\psi) d\sigma \tag{6}$$

With Δg given in Equation (4), where σ denotes the Earth's surface, γ is the normal gravity, and $S(\psi)$ is the Stokes' kernel function.

By rewriting Stokes' equation as a convolution integral in (φ, λ), fast Fourier techniques may be used. In the spherical case (Strang, 1990):

$$N_{\Delta g} = \frac{R\Delta\varphi\Delta\lambda}{4\pi\gamma}\sum_{\varphi}\sum_{\lambda} F^{-1}(F(\Delta g)F(S(\psi))) \tag{7}$$

Where F and F^{-1} are the Fourier and the inverse Fourier transform, respectively. Stokes' function, $S(\psi)$, is defined by:

$$S(\psi) = \frac{1}{\sin\frac{\psi}{2}} - 4 - 6\sin\frac{\psi}{2} + 10\sin^2\frac{\psi}{2} + \left(3 - 6\sin^2\frac{\psi}{2}\right)\ln\left(\sin\frac{\psi}{2} + \sin^2\frac{\psi}{2}\right) \tag{8}$$

Where;

$$\sin^2\frac{\psi}{2} = \sin^2\frac{\varphi - \varphi_P}{2} + \sin^2\frac{\lambda - \lambda_P}{2}\cos\varphi_P\cos\varphi \tag{9}$$

Where φ_P, λ_P is the computation point. Part of the last term in Equation (9) is approximated by:

$$\begin{aligned}\cos\varphi_P\cos\varphi &= \cos^2\frac{\varphi_P + \varphi}{2} - \sin^2\frac{\varphi_P - \varphi}{2} \\ &\approx \cos^2\varphi_m - \sin^2\frac{\Delta\varphi}{2}\end{aligned} \tag{10}$$

Where φ_m is the mean latitude for the area.

The residual anomaly remains in the gravity data after subtracting out the contributions of residual-terrain and global-field effects. The gravity data use the datasets described in the section "Gravity Data". The residual gravity is transformed into the residual geoid by the four-band spherical FFT method (Forsberg and Sideris, 1993), which provides an almost exact implementation of Stokes' formula on a sphere (Schwarz et al., 1990).

The high-frequency part $N_{Terr-eff}$ of the geoid is the terrain effect on the geoid generated by the gravimetric reduction method using a DEM. The RTM terrain reduction method evaluates the gravitational effects of mass anomalies relative to a mean elevation surface, which is determined by moving-average filtering using local DEM data (Tscherning et al., 1994).

In the principle of the RTM methods used to estimate the quasigeoid the free-air anomaly, Δg_{FA} and Equation (4) refers to the surface of the topography, and Stokes' formula is substituted by the Molodensky integral, which yields the residual quasigeoid height (height anomaly):

$$\zeta_{\Delta g} = \frac{R}{4\pi\gamma}\iint(\Delta g + g_1)S(\psi)\cos\varphi d\varphi d\lambda \tag{11}$$

Where φ, λ are geographical coordinates, γ is the normal gravity at the surface, g_1 is the first term in the Molodensky expansion, and Δg_{FA} refers to the surface of the topography. The final quasigeoid is obtained by:

$$\zeta = \zeta_{GGM} + \zeta_{\Delta g} + \zeta_{Terr-eff} \tag{12}$$

Where $\zeta_{\Delta g}$ is the residual height anomaly; $\zeta_{Terr-eff}$ is the terrain effect on the quasigeoid.

The RTM geoid effect is expressed as:

$$\begin{aligned}\zeta_{Terr-eff} = \zeta_{RTM} &= \frac{G\rho}{\gamma}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{h_{ref}}^{h}\frac{1}{r}\,dxdydz \\ &= \frac{G\rho(h-h_{ref})}{\gamma}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{r_0}\,dxdy\end{aligned} \tag{13}$$

The aforementioned linear expression is readily evaluated by FFT methods (Forsberg 1985). The mean elevation surface corresponds, in principle, to the topographic signal already present in the spherical-harmonic reference model. The terrain effect was calculated by the RTM method, which was found to be the most suitable for calculating topographic effect in the geoid determination of Korea (Lee et al., 2010), using a mean DEM surface with approximately 1′ × 1′ grid spacing and a Korean local DEM regenerated from Shuttle Radar Topography Mission (SRTM) data (SRTM, 2000). In the present case the mean DEM surface of approximately 75 km (42′ × 58′) resolution was used. The practical implementation of the RCR technique involves certain approximation in the evaluation of the topographic, atmospheric, and ellipsoidal effects, which are discussed in, for example, Sjöberg (2005), and should be considered to achieve a 1-cm geoid model. The investigation of the magnitudes of the adopted approximation in computing the regional geoid model is left to a future research and will not be considered in this study.

The separation between quasigeoid and geoid, which is required to obtain the geoid from the quasigeoid in the RTM method can be computed from (Heiskanen and Moritz, 1967):

$$\zeta - N = -\frac{\bar{g}-\bar{\gamma}}{\bar{\gamma}}h \approx \frac{\Delta g_B}{\bar{\gamma}}h \tag{14}$$

Where $\bar{g}$, $\bar{\gamma}$, and Δg_B represent the mean gravity, normal gravity, and Bouguer anomaly, respectively.

Thus, the gravimetric geoid heights over Korea were computed by the RCR technique with the application of a two-dimensional four-band spherical FFT transformation on reduced-gravity data followed by the restoration of terrain effects and the EIGEN-GL04C-model effect. Data were gridded in the area of 33°N to 39°N by 124°E to 131°E at a basic grid spacing of 1′ × 1′ in latitude and longitude. The FFT was performed using 100% zero padding to limit periodicity effects and the computation of the geoid was done with the GRAVSOFT software developed by Tscherning et al. (1994). The final gravimetric geoid model is named JNUGEOID2010, and Figure 4 shows the resulting distribution of geoid heights from this model.

RESULTS

To evaluate the accuracy of the JNUGEOID2010 model, the model geoid heights were compared with the GPS-levelling-derived geoid heights from the 735 benchmarks broadly distributed over Korea. To check whether JNUGEOID2010 provides an improvement over KGEOID98 (the Korean national geoid model), KGEOID98 was also compared with the same GPS-levelling-derived geoid heights. Finally, to evaluate the performance of EGM2008, its geoid computed to degree and order 2190, which is shown Figure 5, was compared with the same GPS-levelling-derived geoid heights. The statistics of these geoid-height differences ($N_{Model} - N_{GPS/Leveling}$) before and after bias removal are compiled in Table 6, and the GPS-levelling-derived geoid heights are shown in Figure 6. Figure 7 shows the geographic picture of the differences (in metres) in geoid heights (bias not removed) between KGEOID98, JNUGEOID2010, and EGM2008 and the GPS-levelling-derived geoid heights. These results indicate that significant improvements are obtained with the new models, with the best model being EGM2008, followed by JNUGEOID2010 and then KGEOID98.

JNUGEOID2010 provides a major improvement over KGEOID98 because the standard deviation of JNUGEOID2010 before bias removal is reduced by about 26% compared with that of KGEOID98. EGM2008 exhibits some improvement over JNUGEOID2010 because the standard deviation of the former is about 10% less than that of the latter. JNUGEOID2010 is a new regional geoid model in Korea, so it should be better than any GGM, but in this case we can see that EGM2008 is better than JNUGEOID2010. We judged that the residual geoid $N_{\Delta g}$ may have some inaccuracies caused by the very sparse and inconsistent gravity data, and this inaccurate residual geoid may affect the accuracy of the short wavelength geoid ($N_{Terr-eff}$) and gravimetric geoid (N_{Grav}). These unusual results could be a problem not only in Korea but also in developing countries suffering

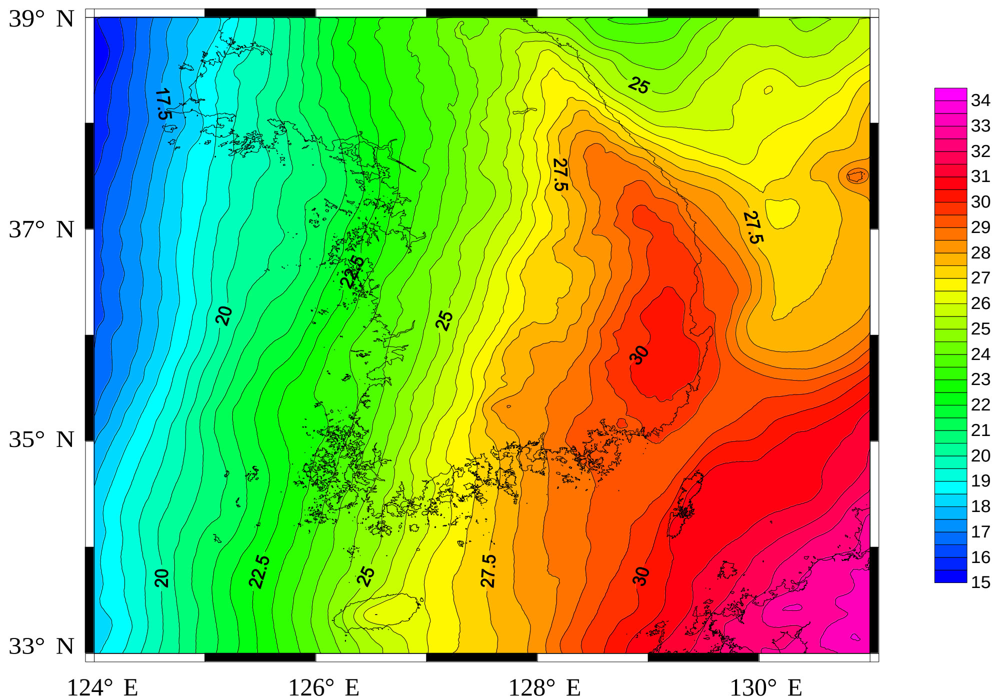

Figure 4. Geoid heights of JNUGEOID2010 regional geoid model over Korea.

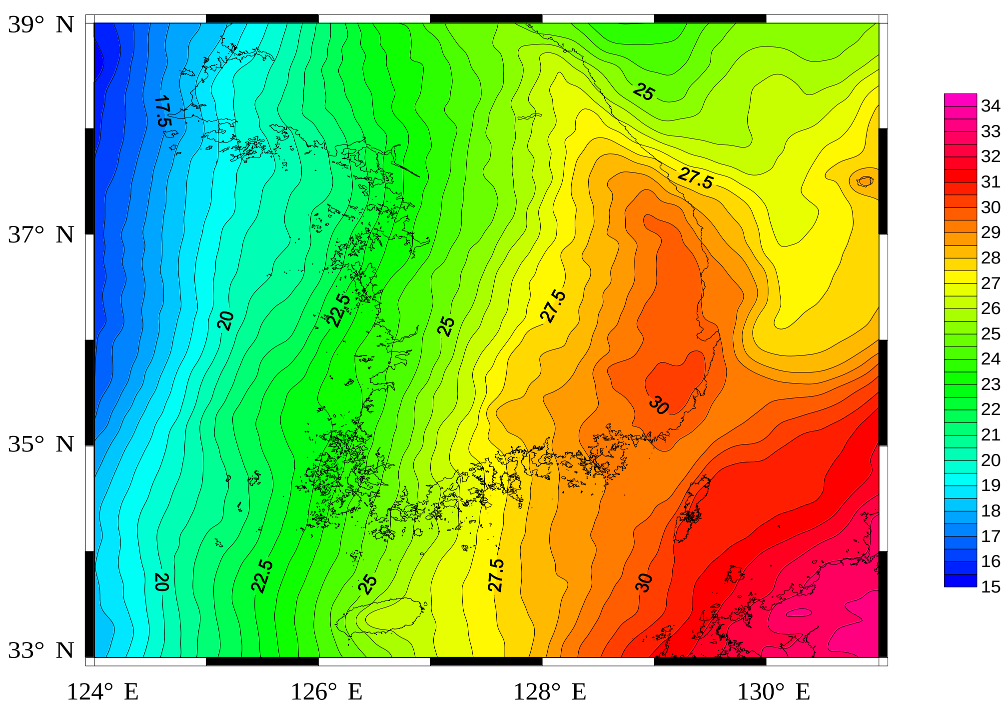

Figure 5. Geoid heights of EGM2008 (2190) over Korea.

from lack of accuracy and density of terrestrial data and this difference will be a subject for further investigations.

The data given in Tables 5 and 6 shows that EGM2008 provides a major improvement over the EGM96 and

Table 6. Statistics of geoid height differences $(N_{Model} - N_{GPS/Leveling})$ (m).

Model	Bias not removed				Bias removed			
	Min.	Max.	Mean	Std dev.	Min.	Max.	Mean	Std dev.
KGEOID98	−0.964	0.964	−0.200	0.243	–	–	–	–
JNUGEOID 2010	−0.870	0.645	−0.126	0.180	–0.265	0.586	0.000	0.052
EGM2008 (2190)	−0.930	0.715	−0.121	0.163	–0.263	0.587	0.001	0.052

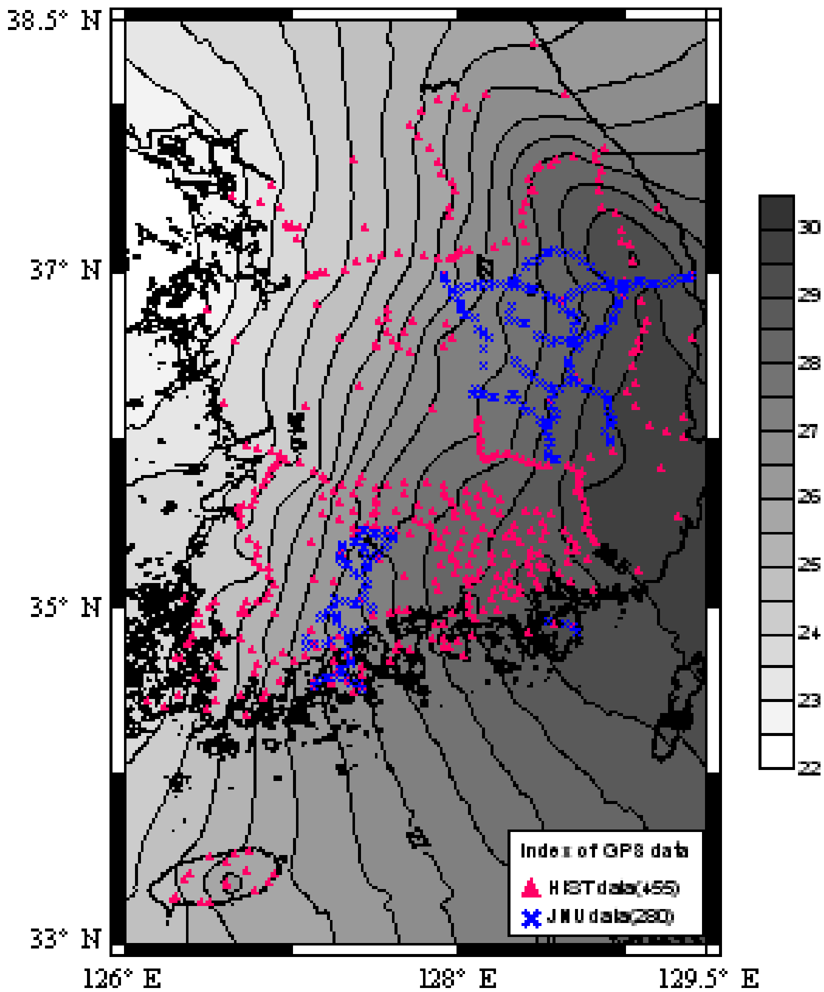

Figure 6. GPS-levelling-derived geoid heights from 735 benchmarks.

EIGEN-GL04C GGMs. It is apparent that, of all the gravimetric geoid models and GGMs considered in this study, EGM2008 gives the best fit over Korea to the GPS-levelling geoid heights.

CONCLUSION

This article presents a regional gravimetric geoid model and an evaluation of the EGM2008 global gravity-field model over Korea by comparing it with GPS-levelling geoid heights. The JNUGEOID2010 model is an improved gravity-field model that is constructed by combining terrestrial gravity data and data from the altimetry-derived marine gravity model DNSC08 with EIGEN-GL04C by the RCR technique. The rationale for this strategy is that EIGEN-GL04C is more accurate than the other four GGMs. To check whether the

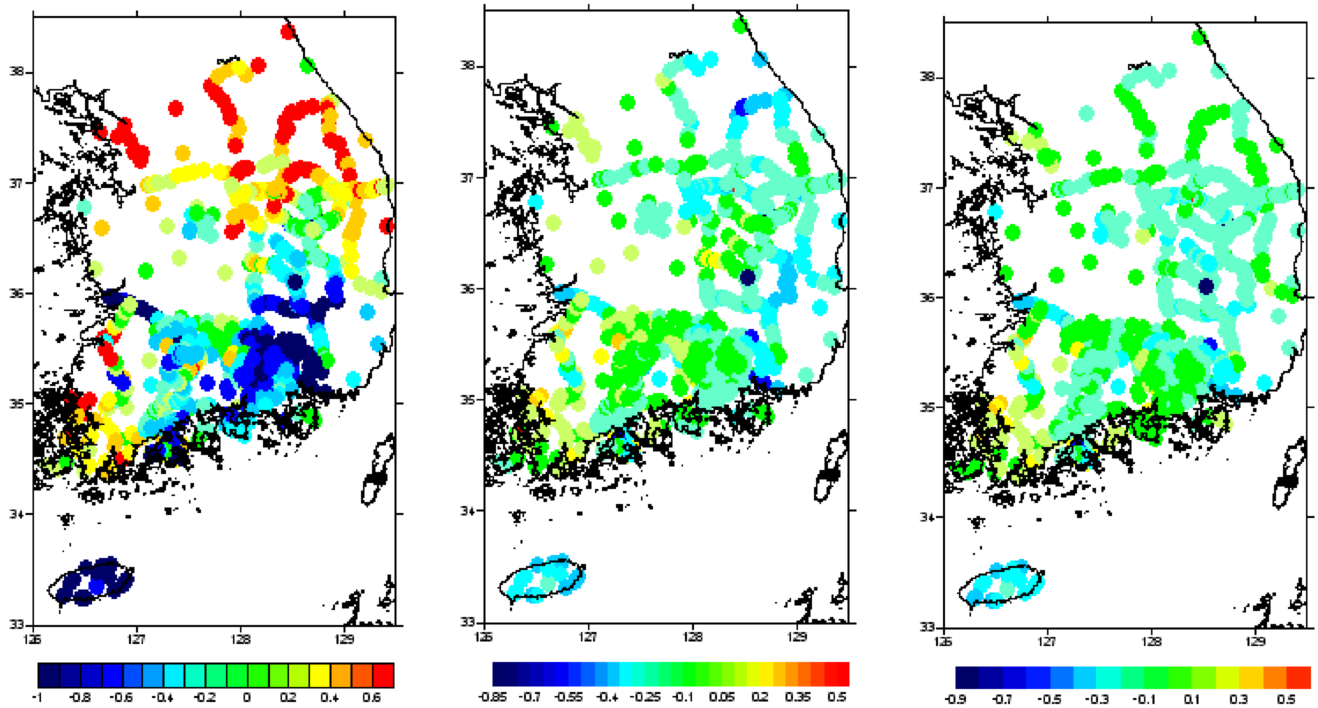

Figure 7. Geoid height differences (m) after subtracting GPS-levelling-derived geoid heights from KGEOID98 (left panel), JNUGEOID2010 (centre panel), and EGM2008 (right panel).

JNUGEOID2010 model provides any improvements, the results of this model are compared with those of KGEOID98. For the comparison, GPS-levelling-derived geoid heights from 735 benchmarks are used, and the smallest bias and standard deviation of geoid height differences are –0.121 and ±0.163 m respectively for EGM2008 to degree and order 2190. Comparisons with GPS-levelling data indicate clearly that the new EGM2008 solution performs better over Korea than the two gravimetric models JNUGEOID2010 and KGEOID98. Thus, we conclude that EGM2008 is slightly superior to the new gravimetric geoid model developed in this study. Further, we know that the density of the terrestrial gravity data that will be employed to compute future national geoid models in Korea should be improved. Also, a computation methodology that optimally combines heterogeneous data, with particular emphasis on the modelling of systematic errors, datum inconsistencies, and propagation of random errors, should be employed to develop a precise Korean geoid model.

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