CALCULATION OF COMPLETE BOUGUER ANOMALIES USING VARIOUS MARINE GRAVITY MODELS IN AREA OF EAST SEA

*Taejun JUNG [a], Hongsik YUN [b], Dongha LEE [*c] and Minwoo PARK [d]*

[a]Ph.D. Candidate, Dept. of Constructional & Environmental System Eng., Sungkyunkwan University, Suwon 440-746, Korea; Tel: + 82-31-290-7522; Fax: +82-31-290-7549;E-mail: tjun97@skku.edu

[b]Professor, School of Civil & Environmental Eng., Sungkyunkwan University, Suwon 440-746, Korea; Tel: + 82-31-290-7522; Fax: +82-31-290-7549; E-mail: yoonhs@skku.edu

[c]Adjunct Professor, College of Engineering, Sungkyunkwan University, Suwon 440-746, Korea; Tel: + 82-31-290-7522; Fax: +82-31-290-7549; E-mail: dhlee.skku@gmail.com

[d]M.D. Candidate, Dept. of Constructional & Environmental System Eng., Sungkyunkwan University, Suwon 440-746, Korea; Tel: + 82-31-290-7522; Fax: +82-31-290-7549;E-mail: pmw0396@skku.edu

KEY WORDS: Free-air Anomaly, Bouguer Anomaly, Complete Bouguer Corrections, Marine Gravity Model

ABSTRACT: This paper describes the results of complete Bouguer anomalies computed from the Free-air anomalies that derived from Sandwell and DNSC08 marine gravity models. Complete bouguer corrections consist of three parts: the bouguer correction (Bullard A), the curvature correction (Bullard B) and the terrain correction (Bullard C). These all corrections have been computed over the East Sea on a 1'× 1' elevation data (topography and bathymetry) derived from ETOPO1 global relief model. In addition, a constant topographic (sea-water) density of 2,670 kg/m^3 (1,030 kg/m^3) has been used for all correction terms. The distribution of complete bouguer anomalies computed from DNSC08 are -34.390 ~ 267.925 mGal, and those from Sandwell are -32.446 ~ 266.967 mGal in East Sea. The mean and RMSE value of the difference between DNSC08 and Sandwell is 0.036 ± 2.373 mGal. The highest value of complete bouguer anomaly are found around the region of 42 ~ 43°N and 137 ~ 139°E (has the lowest bathymetry) in both models. These values show that the gravity distribution of both models, DNSC08 and Sandwell, are very similar. They indicate that satellite-based marine gravity model can be effectively used to analyze the geophysical, geological and geodetic characteristics in East Sea.

1. INTRODUCTION

In general, the gravity anomaly is the difference between the measured gravity at a particular location and the theoretical gravity given by a reference earth model (e.g. GRS80) for the same location. It is widely used in the study of density inhomogeneities inside the Earth. Measured gravity data contain the effects of latitude, Earth tides, instrumental drift, distance from the reference ellipsoid, and masses between the actual topography and the reference ellipsoid. In order to obtain anomalies that are comparable over large areas, a number of corrections must be applied. These are commonly referred to as earth tides, instrumental drift, latitude, free-air and topography corrections. When the first four corrections are applied to measured gravity data we obtain the free-air gravity anomaly, which at short wavelengths correlates strongly with topography. The end-product of all gravity corrections is the complete bouguer anomaly, which should correlate mainly with lateral density variations within the crust and Moho topography. The complete bouguer anomaly is readily obtained by applying the correction for the gravitational attraction of topography to the free-air anomaly. The main purpose of the complete Bouguer correction is to remove all non-geological components of the gravity anomalies enhancing subsurface mass variations (Fullea et al., 2008).

The gravity anomaly on the marine area can be easily obtained from marine gravity models however most of the marine gravity models were developed using satellite data which provide a free-air anomaly on the marine area, not a bouguer anomaly as a gravity anomaly. DNSC08(Anderson et al., 2010) and Sandwell model(Sandwell et al., 2009) are representative models among the many existing marine gravity models that also provide the value of free-air anomaly in the marine and offshore area.

Therefore, the free-air anomaly from marine gravity models should be converted to complete bouguer anomaly for studying the geophysical characteristics on the marine area precisely and applying those results of geophysical study to the geodetic purposes such as determination of marine geoid, geological survey etc. In this paper, we computed the complete bouguer anomalies in the area of East Sea using the free-air anomalies derived from two representative models (DNSC08 and Sandwell) with the gravity corrections of Bullard method (Bullard, 1936). Finally, we also compared the distribution and differences of complete bouguer anomalies between results of two models in order to improve the geophysical, geological and geodetic capabilities of marine gravity models in East Sea.

2. THEORITICAL BACKGROUND OF COMPLETE BOUGUER CORRECTIONS

The topography or complete Bouguer correction has been historically performed in three steps: the Bouguer slab correction (Bullard A), which approximates the local topography (or bathymetry) by a slab of infinite lateral extent, constant density and thickness equal to the elevation of the point with respect to the mean sea level; the curvature correction (Bullard B), which replaces the Bouguer slab by a spherical cap of the same thickness to a distance of 166.735 km; and the terrain correction (Bullard C), which consists of the effect of the surrounding topography above and below the elevation of the calculation point (Nowell, 1999). These corrections to produce the bouguer anomaly are not gravity reductions, in that the gravity value is not somehow moved or ‘‘reduced’’ to a different location, as station values remain fixed at the point of observation. The Bouguer slab below the gravity station pulls downwards and increases the observed value of gravity: hence this effect has to be subtracted from readings. According to this method, the complete bouguer anomaly (Δg_{CBA}) at the specific point *P* can be expressed with Bullard correction terms;

$$\Delta g_{CBA} = \Delta g_{FA} + B.A + B.B + B.C \tag{1}$$

where, Δg_{FA} is free-air anomaly at *P* and the terms of *B.A*, *B.B*, *B.C* are presented to Bullard A, B and C corrections respectively.

The Bullard A (B.A) correction is so called bouguer correction which approximates the topography to an infinite horizontal thickness equal to the height of the station above sea level or any other datum plane. The formula for the *B.A* is:

$$B.A = 2\pi G\rho h \tag{2}$$

where, *G* is the gravitational constant (typically 2,670 kg/m^3), ρ is the density of the surface layer and *h* is the thickness of the slab.

The curvature correction, Bullard B (*B.B*), out to 166.735 km consists of two parts: the section of the spherical cap directly underlying the infinite slab which dominates up to elevations of 4.150 km and pulls downwards increasing the observed value of gravity; and the truncation of the infinite Bouguer slab at 166.735 km which dominates at elevation above 4.150 km and decreases the observed value of gravity. *B.B* correction accounts for the curvature of the Earth by replacing the infinite Bouguer slab with a spherical cap of the same thickness, a radius of 6731km and width R_d. In this work, we use the approximation of Whitman (1991) for calculating the *B.B* correction, which is accurate to 10^{-3} mGal for a slab of thickness up to 4 km. It represents a great simplification over the exact formula and can be interpreted physically in terms of fractions of the *B.A* correction. According to this author, the *B.B* correction can be expressed in terms of the elevation at the calculation point, h, as

$$B.B = -2\pi G\rho h(\frac{\alpha}{2} - \frac{\eta}{2\alpha} - \eta);\quad \alpha = \frac{R_d}{R_T};\ \eta = \frac{h}{R_T + h} \tag{3}$$

where R_T is the radius of a spherical Earth. The value for Rd is usually set to 166.735 km, which coincides with the outer limit of the Hayford-Bowie system (Hayford and Bowie, 1912). This particular value of R_d minimizes the difference between the effect of the spherical cap and the infinite horizontal Bouguer slab, and hence, it should be assumed as a standard distance for *B.B* correction (LaFehr, 1991).

The terrain correction, Bullard C (B.C), which takes into account the undulations of the topography above and below the curved surface of the Earth at the height of the station. The terrain correction is always positive for land points, while for offshore points it can be either positive or negative. It is by far the most time demanding and tedious task of the three steps. Traditionally, terrain corrections were carried out manually using the method of Hammer (1939), which divides the surrounding area into compartments (cylindrical sectors) and compares their elevation with the elevation of the station. Along with the advancements in computer speed and digital elevation models (DEM) during the early 60s, new techniques have been developed for land terrain corrections. Analytical methods decompose the topography in a set of elementary bodies whose gravity effect is well known (Fullea et al., 2008). Numerical methods approximate the exact solutions for the gravity attraction using different numerical schemes, e.g. Fast Fourier Transform, FFT (Forsberg, 1985; Parker, 1996; Tsoulis, 2001) or Gaussian quadrature (Hwang et al., 2003). One of the main limitations of the DEM-based techniques, which usually consider an average value over each cell of the model, is the omission of the near-meter effects, which can account for several mGals, depending on the roughness of the topography and the spatial resolution of the DEM (Leaman, 1998; Nowell, 1999).

A new method for terrain correction was suggested by Fullea et al (2008), this method performs *B.C* corrections using a gridded DEM at specific region, defining several zones depending on the horizontal distance (*R*) to the point where bouguer anomaly is to be calculated, and also whether this calculation point is onshore or offshore. For offshore areas, this method defines three zones: an inner zone, an intermediate zone and a distant zone. To exploit the availability of more detailed DEM in onshore areas, the program offers the possibility to redefine the inner zone as and add a new detailed intermediate zone to the calculation. Each zone has its own grid step and calculation method (Fullea et al., 2008). *B.C* correction according to Fullea method can be expressed as:

$$B.C = \Delta g_D + \Delta g_I + \Delta g_{IN} \tag{4}$$

where Δg_D is the contribution of the topography in the distant zone, Δg_I is the contribution of the topography in the intermediate zone, Δg_{IN} is the contribution of the topography in the inner zone.

3. COMPUTATION OF COMPLETE BOUGUER ANOMALY IN EAST SEA

In this work, we calculated complete bouguer anomalies using the free-air anomaly obtained from marine gravity model (DNSC08 and Sandwell) and Global relief model (ETOPO1) in the offshore area of East Sea. Fullea method is mainly intended for regional grid-based computations, and hence the format of the input files is particularly suitable for the use of publicly available global gridded Δg_{FA} and elevation data sets (Sandwell and Smith, 1997).

With the aim of calculating a complete bouguer anomaly of the study region, we have integrated two available marine gravity models, DNSC08 and Sandwell model. DNSC08 (Andersen et al., 2010) is made by a new retracking techniques of the radar altimetry has been processed using EGM2008 as reference and augmented with ArcGP gravity data and laser altimetry from ICESat to close the Polar gap. DNSC08GRA is seen to perform significantly better than previous global marine gravity field like KMS02. The improvement in accuracy is better than 20% in general, but in coastal regions, the improvement is in many places of the order of 40–50% compared to older global marine gravity field KMS02. Sandwell model (Sandwell et al., 2009) has 1´ × 1´ resolution (approximately 2 km × 2 km). The accuracy of the satellite-derived gravity anomaly is 4 - 7 mGal.Comparisons between shipboard gravity and the global gravity grid show errors ranging from 2.0 mGal in the Gulf of Mexico to 4.0 mGal in areas with rugged seafloor topography. The largest errors of up to 20 mGal occur on the crests of narrow large seamounts.

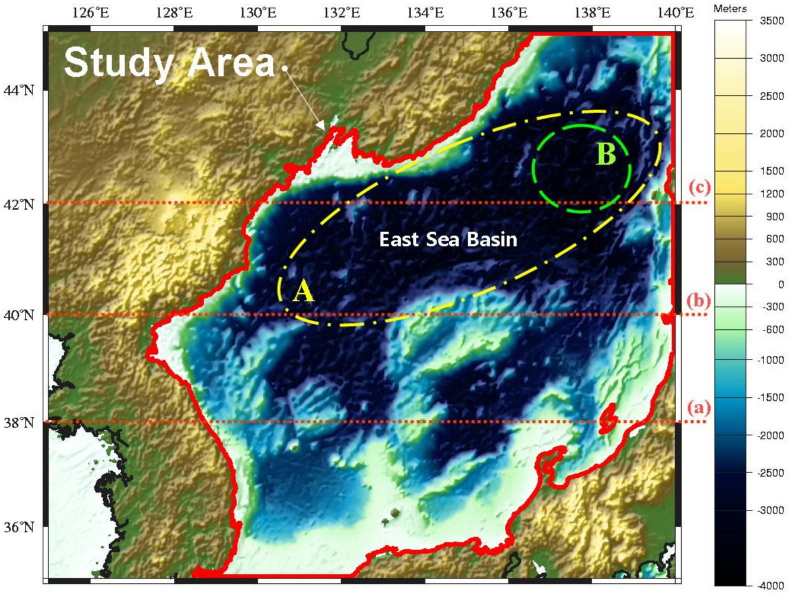
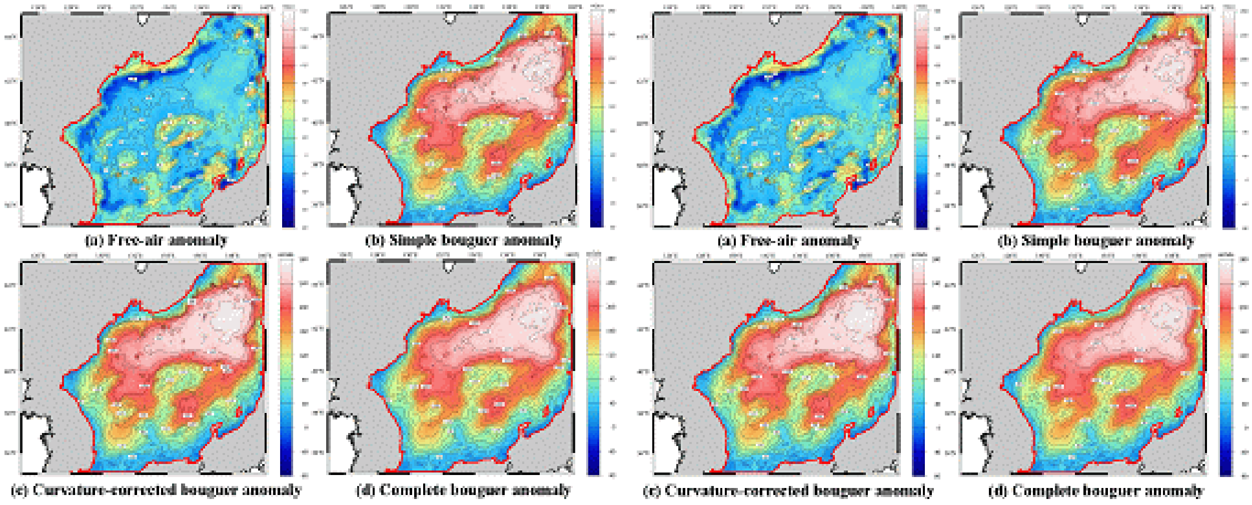


Figure 1. Distribution of topography in study area (inside red line)

For the detailed topography (bathymetry) in East Sea, we have used a detailed topography grid extracted from ETOPO1 model (Hastings et al., 1998). ETOPO1 was developed to improve the resolution and accuracy of the ETOPO2v2 2 arc-minute Global Relief Model, and was designed to support tsunami forecasting, modeling and warning, as well as ocean circulation modeling and Earth visualization. The best available regional and global digital data sets were obtained by NGDC and shifted to common horizontal and vertical datums (Amante et al., 2009). The vertical accuracy of these data is characterized by an RMS error of 18m onshore and of 200m offshore (Fullea et al., 2008).

The complete bouguer anomaly in East Sea was calculated using Bullard corrections according to Fullea method with the input parameters suggested in Fullea et al (2008): Topography (and Sea water) density is 2,670㎏/㎥ (and 1,030 ㎏/㎥, limit of the distant zone is 167㎞ and limit of intermediate zone is 20㎞ etc. The use of a constant density for the topography instead of a variable density model can distort the resulting bouguer anomaly (Flis et al., 1998). However, since a well-constrained regional density model of the study region is not yet available, we have prefer to use the standard constant value of 2670 kg/m^3. The resulting distribution of Bullard corrections (*B.A*, *B.B*, *B.C*) and complete bouguer anomaly of East Sea is shown in Figure 2.


(a) Free-air anomaly
(b) Simple bouguer anomaly
(c) Curvature-corrected bouguer anomaly
(d) Complete bouguer anomaly

A. DNSC08 model

(a) Free-air anomaly
(b) Simple bouguer anomaly
(c) Curvature-corrected bouguer anomaly
(d) Complete bouguer anomaly

B. Sandwell model

Figure 2. Distribution of complete bouguer anomalies in East Sea calculated from marine gravity models

Table 1. Statistics of gravity anomalies in East Sea calculated from marine gravity models

Models	Gravity anomaly (mGal)	Max.	Min.	Mean	std. dev.	RMSE
Sandwell	Free-air	141.770	-58.337	9.179	±22.225	±24.0459
	After Bullard A	268.375	-32.988	138.277	±75.587	±158.026
	After Bullard B	271.546	-32.983	139.863	±77.636	±159.966
	Complete bouguer anomaly	266.967	-32.446	138.831	±75.717	±158.136
DNSC08	Free-air	134.734	-56.392	9.215	±22.033	±23.883
	After Bullard A	269.152	-34.870	138.263	±76.673	±158.099
	After Bullard B	272.323	-34.867	139.899	±77.723	±160.040
	Complete bouguer anomaly	267.925	-34.390	138.867	±75.793	±158.204

The distribution of complete bouguer anomalies computed from DNSC08 are -34.390 ~ 267.925 mGal, and those from Sandwell are -32.446 ~ 266.967 mGal in East Sea. The mean and RMSE value of the difference between DNSC08 and Sandwell is 0.036 ± 2.373 mGal. The highest value of complete bouguer anomaly are found around the region of 42 ~ 43°N and 137 ~ 139°E (has the lowest bathymetry) in both models.

4. CONCLUSIONS

This paper describes the results of complete Bouguer anomalies computed from the Free-air anomalies that derived from Sandwell and DNSC08 marine gravity models. Complete bouguer corrections consist of three parts: the bouguer correction (Bullard A), the curvature correction (Bullard B) and the terrain correction (Bullard C). These all corrections have been computed over the East Sea on a 1'×1' elevation data (topography and bathymetry) derived from ETOPO1 global relief model. In addition, a constant topographic (sea-water) density of 2,670 kg/m^3 (1,030 kg/m^3) has been used for all correction terms.

The distribution of complete bouguer anomalies computed from DNSC08 are -34.390 ~ 267.925 mGal, and those from Sandwell are -32.446 ~ 266.967 mGal in East Sea. The mean and RMSE value of the difference between DNSC08 and Sandwell is 0.036 ± 2.373 mGal. The highest value of complete bouguer anomaly are found around the region of 42 ~ 43°N and 137 ~ 139°E (has the lowest bathymetry) in both models. These values show that the gravity distribution of both models, DNSC08 and Sandwell, are very similar. They indicate that satellite-based marine gravity model can be effectively used to analyze the geophysical, geological and geodetic characteristics in East Sea.

REFERENCES

Amante, C. and Eakins, B. W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24.

Andersen, O. B., Knudsen, P. and Berry, P. A. M., 2010. The DNSC08GRA global marine gravity field from double retracked satellite altimetry. Journal of Geodesy, 84 (3), pp. 191-199.

Bullard, E. C., 1936. Gravity measurements in East Africa. Phil. Trans. Roy. Soc. London, 235, pp. 445-534.

Flis, M. F., Butt, A. L. and Hawke, P. J., 1998. Mapping the range front with gravity-are the corrections up to it?. Exploration Geophysics, 29, pp. 378-383.
Forsberg, R., 1985. Gravity field terrain effect computations by FFT. Bull. Geod., 59, pp. 342-360.
Fullea, J., Fernandez, M. and Zeyen, H., 2008. FA2BOUG—A FORTRAN 90 code to compute Bouguer gravity anomalies from gridded free-air anomalies: Application to the Atlantic-Mediterranean transition zone. Computers & Geosciences, 34, pp. 1665-1681.
Hammer, S., 1939. Terrain correction for gravimeter stations. Geophysics, 4 (3), pp. 184-194.
Hastings, D. A. and Dunbar, P. K., 1998. Development and assessment of the global land one-km base elevation digital elevation model (GLOBE). International Society of Photogrammetry and Remote Sensing, Archives, 32 (4), pp. 218-221.
Hayford, J. F. and Bowie, W., 1912. The effect of topography and isostatic compensation upon the intensity of gravity. Bulletin of the American Geographical Society, 44 (6), pp. 464-465.
Hwang, C., Wang, C. G. and Hsiao, Y. S., 2003. Terrain correction computation using Gaussian quadrature. Computers & Geosciences, 29, pp. 1259-1268.
Nowell, D. A. G., 1999. Gravity terrain corrections-an overview. Journal of Applied Geophysics, 42, pp. 117-134.
Parker, R. L., 1996. Improved Fourier terrain correction: Part II. Geophysics, 61 (2), pp. 365-372.
Sandwell, D. T. and Smith, W. H. F., 1997. Marine gravity anomalies from GEOSAT and ERS-1 satellite altimetry. Journal of Geophysical Research, 102, pp. 10039-10054.
Sandwell, D. T. and Smith, W. H. F., 2009. Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate. J. Geophys. Res., 114, B01411, doi:10.1029/2008JB006008.
Tsoulis, D., 2001. Terrain correction computations for a densely sampled DTM in the Bavarian Alps. Journal of Geodesy, 75 (5-6), pp. 291-307.
Whitman, W. W., 1991. A microgal approximation for the Bullard B-earth’s curvature-gravity correction. Geophysics, 56 (12), pp. 1980–1985.