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COMPARISON OF COMPLETE BOUGUER ANOMALIES FROM SATELLITE MARINE GRAVITY MODELS WITH SHIPBORNE GRAVITY DATA IN EAST SEA, KOREA

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COMPARISON OF COMPLETE BOUGUER ANOMALIES FROM SATELLITE MARINE GRAVITY MODELS WITH SHIPBORNE GRAVITY DATA IN EAST SEA, KOREA

Dong Ha Lee and Tri Dev Acharya

Key words: free-air anomaly, complete bouguer anomaly, marine gravity model, shipborne gravity data, East Sea.

ABSTRACT

This paper describes the results of complete bouguer anomalies (B.A) computed from the free-air anomalies (F.A) of Sandwell and DTU13 marine gravity models that derived from satellite altimetry observations in the area of East Sea, South Korea. In order to confirm the usefulness of satellite-derived gravity anomalies to analyze the geophysical, geological and geographical characteristics in East Sea, the results of marine gravity models have been compared with shipborne gravity anomalies obtained from KHOA (Korea Hydrographic and Oceanographic Agency). To calculate the complete B.A, we applied complete bouguer correction which consists of three steps: the bouguer slab correction (Bullard A), the curvature correction (Bullard B) and the terrain correction (Bullard C). All these corrections have been computed over the East Sea with the 1' × 1' bathymetric data derived from ETOPO1 global relief model. In addition, a constant topographic and sea-water density, 2,670 kg/m^3 and 1,030 kg/m^3, has been used for all correction terms according to the location of gravity points respectively. The distribution of complete B.A computed from Sandwell and DTU13 are very similar to each other with similar statistics i.e., mean of around 101.9 ± 42 mGal. But, the differences with the complete B.A. calculated from shipborne gravities are slightly different over the whole study area, especially around Dok-do and Ulleung-do island, and also in the south-eastern part of Ulleung basin. As the final result, both models shows similar difference and variation, but Sandwell model shows little closer precision towards the shipborne observation data than DTU13 model in the study area. Hence, Sandwell model with the proper complete bouguer correction can be used as an alternative in effective application of gravity data to analyze the geophysical, geological and geographical characteristics in those areas which are not covered by shipborne gravity observations in large area of East Sea. But both combined or separately can also be used in case island or abyssal hill structures with higher slope can be avoided.

I. INTRODUCTION

Gravity models are powerful tools for mapping tectonic structures, especially in the deep ocean basins where the topography remains unmapped by ships or is buried by thick sediment. Shipborne gravimetric measurements, using sea gravity meters mounted on gyro stabilized platforms, have been performed around the world for several decades. Due to instrumental errors, navigational errors, and other error sources, significant inconsistencies exist in marine data. In contrast, satellite radar altimetry data offers a near homogenous and global coverage gravity data. Since the Seasat mission of 1978, global marine gravity anomalies of different accuracies and spatial resolutions have been derived from satellite altimetry. Gravity-field accuracy derived from satellite altimetry depends on three factors: altimeter range precision, spatial track density, and diverse track orientation. There are many publicly available anomaly grids available from different projects and missions. Before applying these gravity models, it has to be clear that which one represents accurately the local area under study. This can be done by comparing the available shipborne gravity data with the satellite derived Gravity models, considering that shipborne measurements are accurate. Both of these data can also be combined to determine gravity field over the large area using various methods. Also, the accuracy and interpretation can be improved by applying bouguer anomaly to the available free-air anomaly.

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

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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 anomaly (F.A), which at short wavelengths correlates strongly with topography. The end-product of all gravity corrections is the complete bouguer anomaly (B.A), which should correlate mainly with lateral density variations within the crust and Moho topography. The complete B.A is readily obtained by applying the correction for the gravitational attraction of topography to the F.A. The main purpose of the complete bouguer correction is to remove all non-geological components of the gravity anomalies enhancing sub-surface 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 altimetry data which provide a F.A on the marine area, not a B.A as a gravity anomaly. DTU13 (Anderson et al., 2013) and Sandwell model (Sandwell et al., 2014) are representative models among the many existing marine gravity models that also provide the value of F.A in the marine and offshore area. Therefore, the F.A from marine gravity models should be converted to complete B.A 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 B.A of 1' × 1' resolution in the area of East Sea, South Korea using the F.A derived from two representative models (DTU13 and Sandwell) with the improved bouguer corrections of Bullard method (Bullard, 1936) as proposed by Fullea et al. (2008). Finally, we also compared the distributions and calculated differences between complete B.As of two models and shipborne gravity data to find out which one is precise satellite-derived gravity and can be adopted for the analysis in geophysical, geological and geographical characteristics in East Sea.

II. 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;

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

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

In general, bouguer anomaly changes are the result of density variations at different depths. Negative anomalies are related to low densities, which at large scale can be due to large sediment basins, thick crust, or shallow asthenosphere. Positive Bouguer anomalies denote high density rocks and may be thin crust.

The Bouguer correction is a correction for the attraction of the mass between the gravity station, and the local geoid. The Bullard A correction ($B.A.C$) is so called simple 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 $B.A.C$ is:

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

where, G is the gravitational constant (6.67 × 10 − 11 m^3 s^{-2} kg^{-1}), ρ is the reduced density of the surface layer and h is the thickness of the slab. The value of reduction density depends on the sign of the elevation i.e. land or sea surface:

$$\begin{aligned} \rho &= \rho_c & \quad if\ H > 0 \\ \rho &= (\rho_c - \rho_w) & \quad if\ H < 0 \end{aligned} \tag{3}$$

where, ρ_c is crustal reduction density (2670 kg/m^3) and ρ_w is sea water reduction density (1030 kg/m^3) and H is the elevation of surrounding topography.

The curvature correction, Bullard B ($B.B.C$), 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. $B.B.C$ accounts for the curvature of the Earth by replacing the infinite bouguer slab with a spherical cap of the same thickness, a radius R_T of 6,731 km and width R_d. In this work, we use the approximation of Whitman (1991) for calculating the $B.B.C$, 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 Whitman (1991), the $B.B.C$ can be expressed in terms of the elevation at the calculation point, h, as:

$$
\begin{aligned}
&B.B = -2\pi G\rho_c h(\frac{\alpha}{2} - \frac{\eta}{2\alpha} - \eta); && \mathit{if}\ h < 0 \\
&B.B = -2\pi G(\rho_c - \rho_w)h(\frac{\alpha}{2} + \frac{\eta}{2\alpha} + \eta); && \mathit{if}\ h > 0 \\
&\alpha = \frac{R_d}{R_T}; \\
&\eta = \frac{h}{R_T + h}
\end{aligned}
\tag{4}
$$

where R_T is the radius of a spherical Earth. The value for R_d is usually set to 166.735 km (1.5°), 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.C* (LaFehr, 1991).

The terrain correction, Bullard C (*B.C.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.C* 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 FA2BOUG code 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.C* according to new method in Fullea et al. (2008) can be expressed as:

$$
B.C.C = \Delta g_D + \Delta g_I + \Delta g_{IN} \tag{5}
$$

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.

III. STUDY AREA AND DATA

In this study, the study area was selected from East Sea of Korea where shipborne marine gravity data has been observed by Korea Hydrographic and Oceanographic Agency (KHOA) using various oceanic research vessels. The East Sea is of much importance in terms of geopolitical and economical point of view. The dispute of Dok-do island and its territorial sea as well as maritime ways to Japan and Russia give the area more importance. Similarly, the tides of the East Sea are significantly smaller than those of the Yellow and the South Sea. Also, the area have higher dissolved oxygen and hence fishing is dominant economy which requires a frequent update of the surface and gravity in the area.

The KHOA was established in 1949 as the hydrographic division under the Operations Department of the Republic of Korea Navy. With the inauguration of the Ministry of Maritime Affairs and Fisheries in 1996, it changed to the present name, KHOA. The KHOA conducts maritime surveys for maritime traffic and safety, maritime development and preservation, and the security of sea territory.

Since 1996, KHOA have conducted annual surveys for basic maps of the sea in Korea's jurisdictional sea area. The survey for basic maps of the sea is intended to secure scientific inquiry data needed for systematic marine management, such as boundary delimitation and sea traffic safety in the jurisdictional sea area, marine resource development, and marine policy setup pursuant to the UN Convention on the Law of the Sea.

As a result of maritime survey, from 1996 to 2010, the 1st-phase survey was completed, which covered bottom topography, gravity, terrestrial magnetism, and the shallow subsurface, throughout the eastern, western and southern sea areas totaling 343,000 km^2. Moreover, from 2008, a detailed submarine topographic survey has been conducted in the western and southern sea areas totaling 242,000 km^2. The uncovered areas can be expanded with the help of remote satellites sensors.

The outcomes are used in producing a basic map of the sea, which comprises bathymetric chart, free-air gravity anomaly chart, total magnetic intensity chart, and sub-bottom echo character chart. This basic map is designed for use in research, education, and marine resource development.

Fig. 1 shows the total coverage of KHOA shipborne marine gravity database along with study area in red polygon in East Sea.

The detailed explanation of primary dataset for the study are:

(a) Shipborne marine gravity observations: A total of 616,913 shipborne gravity observations were selected in the study area from whole KHOA gravity database. By considering the quality of satellite-derived gravity models, the study area

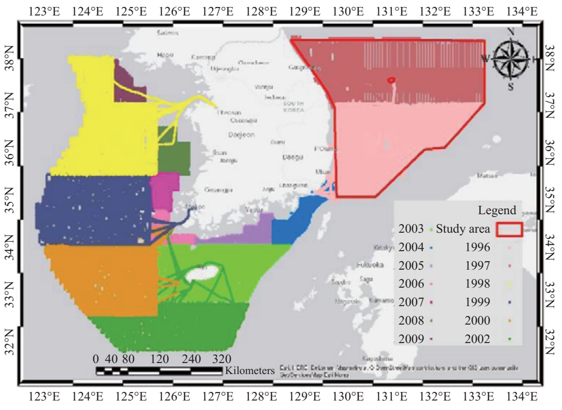


Fig. 1. **Shipborne gravity measurements around Korea (study area inside red line).**

was only selected in the area of East Sea. The quality of satellite derived gravity models are decreased considerably near coastal shelves or in rough bathymetric areas. Such limitations are partly due to altimetric technology, which prevents the exploitation of measurements close to the coastlines and limits the space resolution along the satellite tracks to 7 kilometers after reprocessing. The resolution across track remains unchanged (Louis et al., 2010). In case of Korea, the East Sea is only vast area with smoother bathymetry and higher resolution of altimetric observations than Yellow or South Sea, that overcome limitations of satellite gravity models and provide more precise F.A.

Fig. 2 (a) shows that the detailed distribution of shipborne gravity data in the study area. These gravity data were measured in 1996 and 1997 by KHOA using oceanic research vessel named as *Haeyang 2000*. This research vessel, *Haeyang 2000*, have observed marine gravity data over 150,000 points each year from year 1996 to year 2003.

All shipborne gravity data in this study were processed by following steps according to Keum et al. (2010):

1. Check the time sequence, latitude and longitude position, etc. of shipborne gravity data,
2. Arrangement of the tide level below the pier and meter drift correction of vessel,
3. Elimination of turning points,
4. The time lag correction,
5. Computation of RV's velocities, Heading angles and the Eötvös correction,
6. Kalman filtering of GPS navigation data using cross-over points and finally
7. Computation of F.A. and Cross-over correction using least square adjustment.

(b) ETOPO1: ETOPO1 (http://www.ngdc.noaa.gov/mgg/glo bal/global.html) is a 1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry and is developed by National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA). ETOPO1 was generated from diverse global and regional digital data sets, which were shifted to common horizontal and vertical datum, and then evaluated and edited as needed (Amante and Eakins, 2009). Fig. 2 (b) shows that the distribution of bathymetric information obtained from ETOPO1 in the study area.

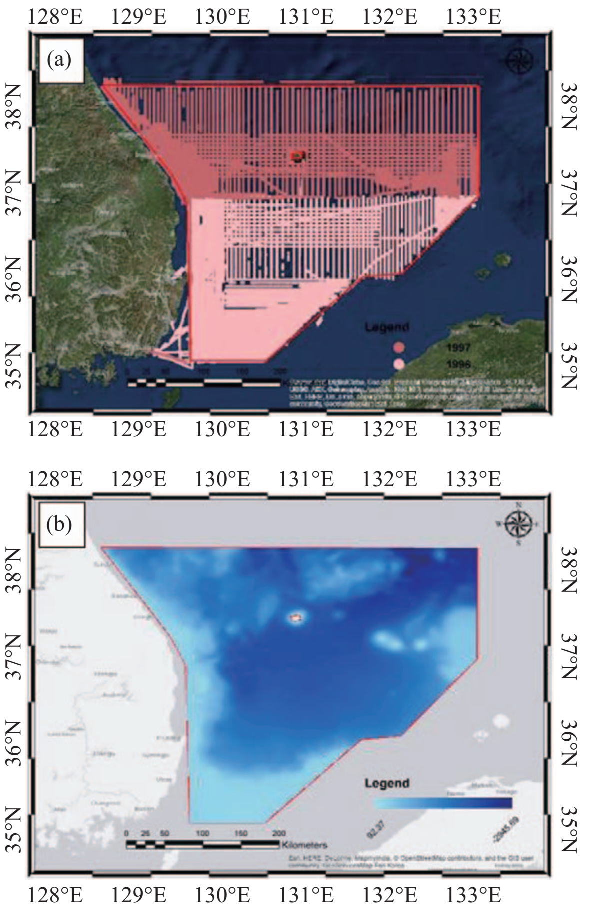


Fig. 2. **(a) Distribution of shipborne gravity points and (b) bathymetry from ETOPO1 in study area.**

(c) DTU13: DTU13 (ftp://ftp.space.dtu.dk/pub/DTU13) is an altimetry-derived marine free-air gravity and mean sea surface dataset, with a resolution of 1 minute by 1 minute corresponding to 2 minute by 2 minute resolution at Equator. DTU13 is a successor of DNSC08 (Andersen and Knudsen, 2009) and DNSC10 (Andersen et al., 2010) brought up by introduction of CryoSat-2 and Jason-1 GM with cross over adjustment and decreasing filtering.

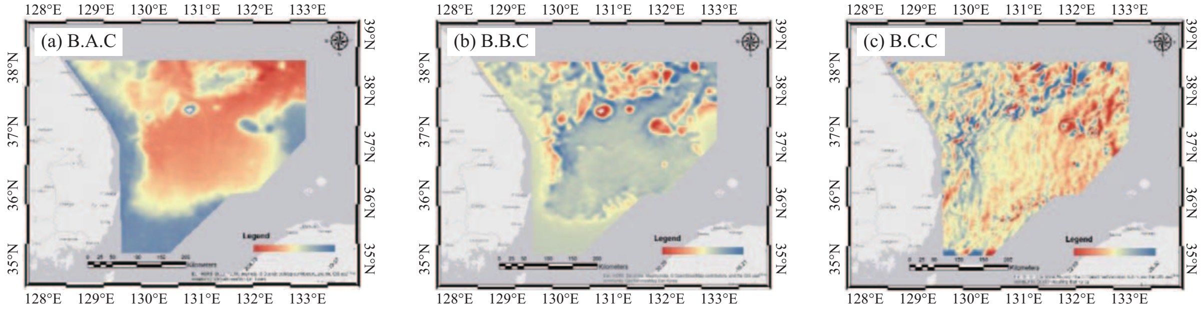
(d) Sandwell v23.1: Sandwell gravity model (ftp://topex.ucsd.edu/pub/global_grav_1min) is a global 1 min grid size satellite gravity data published by Scripps Institution of Oceanography (Sandwell and Smith, 1997; Sandwell and Smith, 2009; Sandwell et al., 2014). The latest available Sandwell model is 23.1 version which is improvement over previous versions. The model was derived by combining new radar altimeter measurements from satellites CryoSat-2 and Jason-1 with existing data to construct a global marine gravity model. It has been found to be two times more accurate than

Table 1. Descriptive statistics of bullard corrections using FA2BOUG. (unit: mGal).

Corrections	Min.	Max.	Mean	Std. Dev.
Bullard A	204.736	-19.976	96.853	50.066
Bullard B	-26.326	22.538	-0.054	3.204
Bullard C	-16.218	30.297	0.709	3.064

Table 2. Descriptive statistics of the gravity anomalies (unit: mGal).

Models	Type of Gravity anomaly	Min.	Max.	Mean	Std. Dev.
Sandwell	F.A	-45.729	110.295	4.415	21.030
	Simple B.A	-0.390	194.343	101.268	43.320
	Curvature-corrected B.A	0.480	193.127	101.214	43.461
	Complete B.A	0.726	194.964	101.923	42.366
DTU13	F.A	-45.729	105.139	4.402	20.971
	Simple B.A	-0.387	195.593	101.254	43.356
	Curvature-corrected B.A	0.489	193.765	101.200	43.498
	Complete B.A	0.735	194.980	101.909	42.893
Shipborne	F.A	-41.864	137.349	8.681	20.418
	Simple B.A	-4.859	216.790	105.274	43.516
	Curvature-corrected B.A	-4.137	221.265	105.220	43.693
	Complete B.A	-2.707	225.403	105.927	43.031



(Unit: mGal)

Fig. 3. Distribution of corrections in study area.

previous models. The 1- to 2-mGal gravity accuracies achieved by Sandwell et al. are based on worldwide comparisons between altimeter gravity and high-quality ship gravity at wavelengths between 12 and 40 km.

For the computation of complete B.A and its comparison with each other, all the input and output gravity and topographic data were resampled into 1' × 1' resolution of grid for the purpose of comparison with masking of land including islands area.

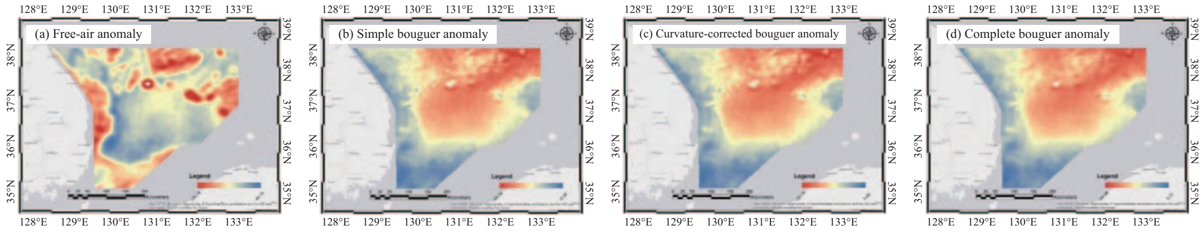
IV. COMPARISION AND DISCUSSION

In this work, we calculated complete B.A using the F.A of marine gravity data (DTU13, Sandwell and shipborne) and bathymetric information obtained from ETOPO1 global relief model in the offshore area of East Sea. The complete bouguer anomaly was calculated by applying Bullard A, B and C corrections to the F.A using the fortran 90 code, FA2BOUG (Fullea et al., 2008), with the suggested input parameters: Topography and sea-water density is 2,670 kg/m^3 and 1,03 kg/m^3 respectively, the limit of the distant zone is 167 km and limit of intermediate zone is 20 km 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 and related statistics of Bullard corrections (*B.A.C*, *B.B.C*, *B.C.C*) of East Sea is shown in Fig. 3 and Table 1.

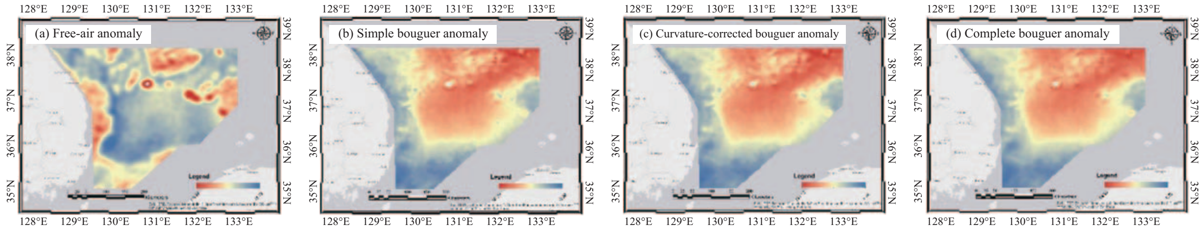
Based on the above calculations, the distribution of complete B.A computed for DTU13,Sandwell and shipborne gravity are shown in Figs. 4-6 respectively along with descriptive statistics in Table 2.

The related statistics from the Table 2 shows that are complete B.A for Sandwell range from 0.726 to 194.964 mGal, and in DTU13 the ranges are 0.735 to 194.980 mGal in study area of East Sea. The mean value of both of the model is 101.9 mGal but the standard deviation is differed slightly by 0.52 mGal.



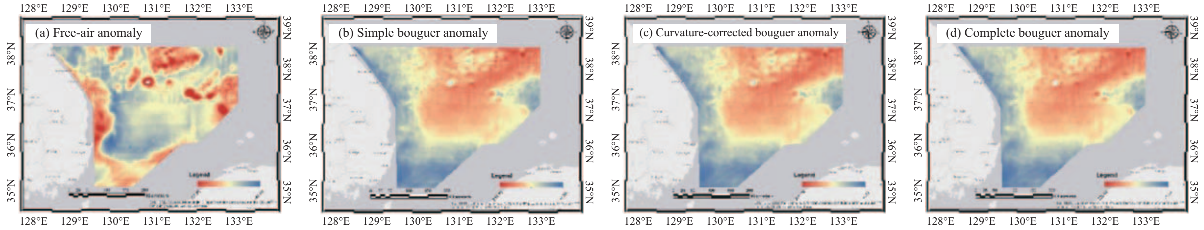
(Unit: mGal)

Fig. 4. Distribution of gravity anomalies in East Sea calculated from DTU13 marine gravity model.



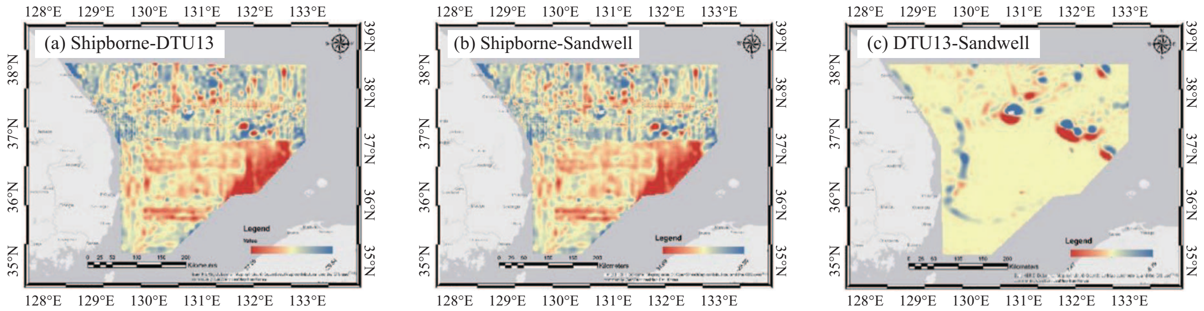
(Unit: mGal)

Fig. 5. Distribution of gravity anomalies in East Sea calculated from Sandwell marine gravity model.



(Unit: mGal)

Fig. 6. Distribution of gravity anomalies in East Sea calculated from Shipborne gravity data.



(Unit: mGal)

Fig. 7. Distribution of complete B.A. differences.

Table 3. Descriptive statistics of difference map (unit: mGal).

Grid Difference	Min.	Max.	Mean	Std. Dev.
Shipborne - Sandwell	-29.357	34.692	4.256	5.998
Shipborne - DTU13	-29.543	37.263	4.269	6.024
DTU13 - Sandwell	-6.797	7.477	-0.014	0.508

Whereas, in case of complete B.A of shipborne gravity data, the minimum value is -2.707 mGal and maximum is 225.403 mGal. The mean and standard ad deviation values are higher i.e., 105.927 mGal and 43.031 mGal respectively.

A difference map can provide a good sight on the difference in the dataset and help in selecting closely accurate dataset. Fig. 7 and Table 3 show the distribution and explanatory statistics of the difference between the calculated complete B.A of all three gravity sources. From Table 3, compared to DTU13, Sandwell shows less statistical variation in all factors while differencing with the shipborne data. This concludes the precision of Sandwell is little closer to the shipborne gravity data.

Even though both anomalies from marine gravity models have higher difference with shipborne gravity data, the difference between DTU13 and Sandwell is quite small of - 6.797 - 7.477 mGal and most of the difference has been seen in the area with island or abyssal hill structures with higher slope.

Gravity observations around the vast sea is not always possible and very few nearby coverage are only available in different countries. Also, It is important to take into account bodies of water, and marine surveys must be converted to Bouguer gravity if they are to be combined with terrestrial data. To compensate the gap, various satellite derived gravity models with global coverage are available from the research groups (Anderson et al., 2013; Sandwell et al., 2014). These data has been compared either in F.A or complete B.A forms in various regions of the world to test the accuracy and further application in vast region. Featherstone (2002) compared three publicly available only altimetry derived gravity anomalies, whereas Keating and Pinet (2013) converted the F.A to complete B.A and compare them with the shipborne data in Hudson Bay region of Canada.

The current study used the comparison of complete B.A form the latest available satellite derived gravity models and compared with the shipborne data to find out that DTU13 and Sandwell shows nearly similar difference with the shipborne gravity, but difference between both models is more in the island or abyssal hill structures with higher slope. Avoiding such coastal areas and abysall hills through masking can give much better results for the marine gravity. In future, with increase in gravity satellites and their coverage, the improvement in satellite derived gravity models can be achieved. Such improve in quality and resolution of publically available gravity models can have great potential to research communities in the field of geophysics, marine geography and geodesy.

V. CONCLUSION

In this study, the F.A of satellite derived marine gravity models, Sandwell and DTU13, as well as shipborne gravity data were processed to develop each complete B.A.

The correction consists of three parts: the bouguer slab correction (Bullard A), the curvature correction (Bullard B) and the terrain correction (Bullard C). These all corrections have been computed over the study area on 1' × 1' resolution of grid. From the outputs, the distribution of complete B.A computed from Sandwell are 0.726 - 194.964 mGal, and those from DTU13 are 0.735 - 194.980 mGal in study area around the East Sea. Although both satellite derived anomalies have higher difference with those of shipborne gravity data, the difference between DTU13 and Sandwell is quite small of - 6.797 - 7.477 mGal and most of the difference has been seen in the area with island or abyssal hill structures with higher slope.

The precision of both Sandwell as well as DTU13 are closer to the shipborne gravity data, but in average Sandwell a little bit better than DTU13. Hence, Sandwell marine gravity model might be more preferable to areas with no shipborne data for analyzing geophysical, geological and geographical explorations, especially in the area of East Sea. But, combined average or anyone of the method would be useful in case the island or abyssal hill structures with higher slope are avoided.

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