Bias-corrected GOCE geoid for the generation of high-resolution digital terrain model

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This study aims at deriving a geoid over India using the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite, evaluate its accuracy and application potential. The main objective is to convert satellite-derived ellipsoid height to orthometric height using geoid derived from GOCE and convert an ellipsoid digital terrain model (DTM) to orthometric DTM for hydrology, flood undulation and coastal management. The study was carried out over two areas, viz. Kosi river basin, Bihar and Mahanadi river basin, Odisha. The results indicate that over a total of 148 benchmarks, the GOCE geoid has a bias of 1.5 m with reference to the ground geoid. The study also demonstrated that using benchmark data, it is feasible to derive a geoid from GOCE with 10–15 cm accuracy that would meet most of the user requirements.

Keywords: Benchmarks, digital terrain model, geoid, gravity satellite.

THE digital terrain model (DTM) is a statistical representation of the continuous ground surface by a large number of selected points with known *X*, *Y* and *Z* coordinates in an arbitrary coordinates field[1]. The scientific community and commercial market are increasingly aware of the importance of DTM in various applications. These include a large number of environmental, engineering and commercial GIS applications that rely entirely on the ready availability of digital terrain databases[2]. Many of the applications require orthometric terrain height, which is referenced to mean sea level (~geoid) as a corresponding reference surface. These applications include flood inundation modelling, hydrological applications and coastal zone management. DTM generated from air/satellite-borne stereo camera images will directly provide ellipsoidal height, i.e. WGS84, since orbital determination is by the on-board Global Positioning System (GPS) which is referenced to WGS84. Ellipsoidal height is mathematically derived and does not follow Earth's gravity, whereas orthometric height is measured along the plumb line and depends on Earth's gravity. One of the procedures of deriving orthometric height is to use a geoid model which takes WGS84 ellipsoidal heights as input and gives orthometric heights as output. Such an approach would significantly reduce DTM generation time as well as cost. Globally researchers are working on a geoid model that includes EGM96 (ref. 3) and EGM08 (ref. 4) which provide the geoid using earth gravity field knowledge with an accuracy of 1–4 m. EGM96 is an improved spherical harmonic model of the Earth's gravitational potential up to degree and order 360, which corresponds to the spatial resolution of 55 km. It incorporates improved surface gravity data, altimeter-derived anomalies from ERS-1 and GEOSAT geodetic mission, satellite tracking data from SLR, GPS, TDRSS, DORIS, TRANET Doppler tracking system and direct altimeter ranges from Topex/Poseidon, ERS-1 and GEOSAT. The EGM08 Earth gravitational model released by the US National Geospatial Agency in April 2008 is a state-of-the-art high-degree global geopotential model (GGM) of the Earth's external gravity field. It is complete to spherical harmonic degree and order 2,160 and provides some additional spherical harmonic coefficients to degree 2,190. EGM08 incorporates improved 5×5 min gravity anomalies, altimetry-derived gravity anomalies and has benefitted from the GRACE-based satellite solutions. This corresponds to a spatial resolution of 5 arc min or ~9 km. EGM08 has its applications, for example, in improving the quasi geoid computations in the absence of gravity data when combined with residual terrain model data, especially in mountainous areas[5]. However for high-resolution DTM, the height accuracy must be better than 25 cm that includes geoidal and processing accuracy of airborne digital camera or LiDAR so that 1 m contour interval can be generated from the DTM. Hence one requires a highly accurate geoid model.

In India, gravity model is not available/accessible to the user. However, Survey of India (SOI) has established thousands of primary benchmarks (BM) all over the country with known orthometric height. But for a study area of 5000 sq km, only few BMs are available and it is difficult to generate a geoid model for the entire study area. Hence extensive ground levelling needs to be carried out to establish more temporary benchmarks (TBMs) by traversing from the primary BM, measure ellipsoidal height using GPS at those points and generate a geoid model which can be applied to all ellipsoidal heights in those areas. The levelling work involves mobilizing field crew to each BM in the area and obtaining the WGS84 height with GPS. This is not only laborious but also time-consuming and not always feasible, especially in forests and inhospitable terrains.

Before the launch of the gravity satellites CHAMP (2000), GRACE (2002) and GOCE (2009), gravity field models were composed out of many different datasets, including orbits from different (high-flying) satellites, altimeter data over sea, and aerial and terrestrial gravity observations over land. Therefore, the accuracy of these models is not homogeneous over the whole region and the long wavelength parts of the models contain large uncertainties. The gravity missions CHAMP[6], GRACE[7]

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and GOCE[8] are designed to change this. Through their low flying orbits, the long, medium and short wavelength parts of the gravity field model are strengthened[9]. In addition, a homogeneous accuracy is obtained over the particular region, because of the homogeneous distribution of satellite observations. The GOCE system configuration is superior compared to the other two satellites because of the availability of highest sensitivity accelerometers in space, its low altitude and also because it can be detect fine density differences in the crust and oceans of the Earth. The low orbit and high accuracy of the system greatly improve the known accuracy and spatial resolution of the geoid. The goal of the GOCE mission is to model the time-invariant component of the Earth's gravity field to an accuracy of at least 1 mgal for gravity anomalies and 1 cm for the geoid at a spatial resolution of 100 km. Evaluation of the initial GOCE data showed that they helped improve knowledge of the Earth's static gravity field at spatial scales between ~125 and ~110 km, particularly over parts of Asia, Africa, South America and Antarctica, in comparison to the pre-GOCE-era[10]. The final geoid model will provide users with a well-defined data product that will lead to a global height-reference system, which can serve as a reference surface for the study of topographic processes and sea-level change.

The main objective of this study is to compare the geoid derived from GOCE with the ground geoid generated from GPS/TBM over two study areas in the Indian subcontinent, namely Kosi river basin, Bihar and Mahanadi river basin, Odisha, and to bias-correct GOCE geoid with GPS/BMs/TBMs so that a geoid with good accuracy is achieved for DTM generation.

As part of ISRO's Disaster Management Support Programme (DMSP), high-resolution DTM with 25 cm vertical accuracy is being generated for floodplain areas using airborne LiDAR. For these areas, primary BMs from SOI have been taken as reference and levelling survey was carried out to establish more TBMs within the study area typically of size ranging from 5,000 to 12,000 sq. km. Two such test sites of DMSP have been considered for this study. GOCE level-2 products are available via the ESA GOCE user service interface (https://earth.esa.int/web/_guest/dataaccess/browse-dataproducts?p_r_p_564233_524-tag=goce).

To effectively use GOCE data, the GOCE user toolbox (GUT) provided by ESA to facilitate the handling, viewing and post-processing of GOCE level-2 data products is utilized (http://earth.esa.int/gut/; accessed March 2011). NC utilities are used to convert binary files to the desired format (e.g. .csv or .xls; www.unidata.ucar.edu/software/netcdf/fan_utils.html; accessed on March 2011) and basic radar altimeter toolbox (Brat) display is used for visualization of all GUT products (http://earth.esa.int/brat/; accessed on March 2011).

For geoid modelling there exist two methods, i.e. geometric and gravimetric[11]. In the geometric method, GPS measurements are taken at BMs with known orthometric height. The difference between the GPS-derived ellipsoidal height (h) and the orthometric height (H) provides the geoidal height (N) at that point as given below and shown in Figure 1

$$N = h - H. \tag{1}$$

In the gravimetric approach, a uniform grid of geoidal heights over a large area is established. However, it requires a complex numerical integration of gravity anomalies to determine a geoidal height, i.e.

$$N = \frac{R}{4\pi\gamma_0} \iint \Delta g \cdot S(\varphi) \cdot \mathrm{d}\sigma, \tag{2}$$

where R is the mean radius of spherical earth, $\mathrm{d}\sigma$ the surface integration element, $S(\varphi)$ the Stoke's function, and Δg is the gravity anomaly.

Even though the gravimetric method gives good spatial coverage over large areas, it is computationally intensive and mathematically complex. If there are errors in the gravity data, there will be errors in the geoid. Hence the best possible approach would be a combination of the two methods. The gravimetric geoid is computed first, and then 'bias corrected' using GPS-determined geoidal heights at BMs over the study area, i.e. geoid obtained by gravimetric method from GOCE data was bias-corrected with ground geoid. To compute geoid heights from GOCE data, the GUT toolbox was used. The GOCE level-2 product, namely EGM_GOC_2 itself contains geoid heights but at an interval of 30′ × 30′. The geoid heights based on GOCE data are interpolated from the closest grid points using the GUT software.

In the study area, along with orthometric heights, the geographical coordinates of BMs, i.e. latitude, longitude and WGS 84 ellipsoid height were obtained using GPS receivers. The geoid undulation was calculated at each BM using eq. (1) and compared with GOCE geoid. The bias was estimated using BMs/TBMs and the entire GOCE geoid of the study area was corrected. From the bias-

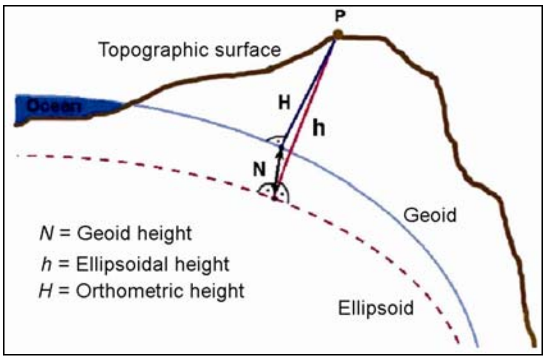

Figure 1. Relation between geoidal, ellipsoidal and orthometric heights.

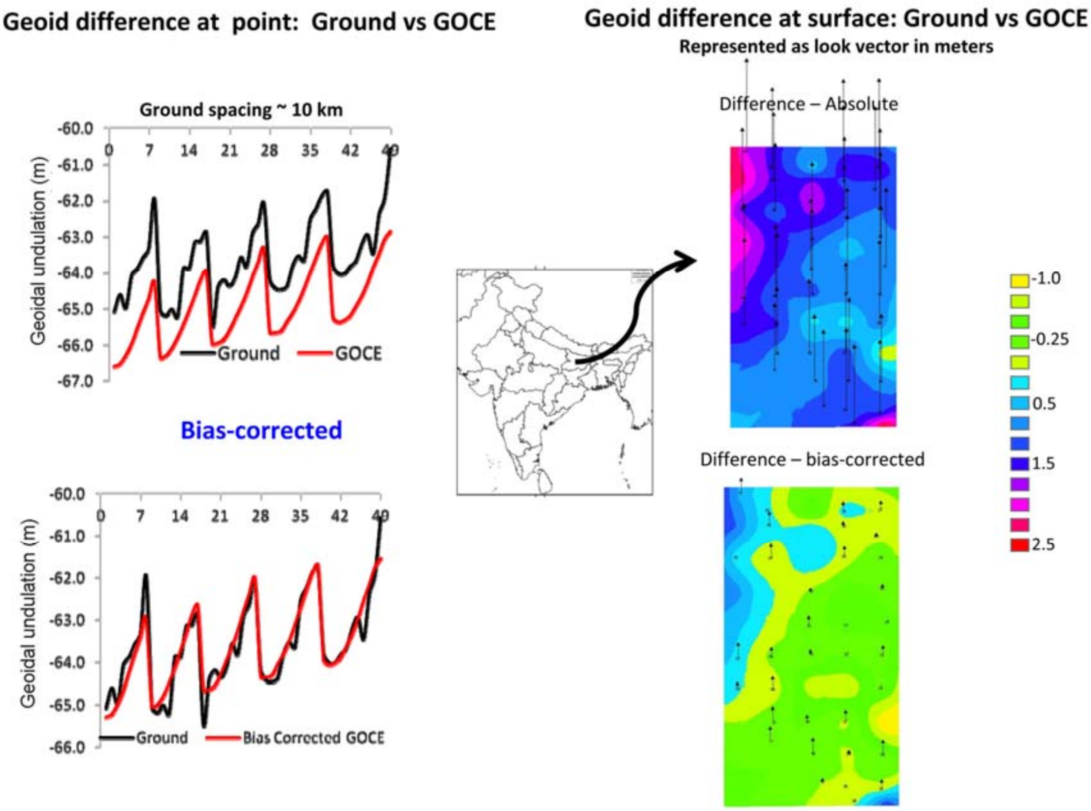

Figure 2. Difference between GOCE and ground data – absolute versus post bias correction of Kosi river basin, Bihar.

Table 1. Geoid undulation difference: GOCE versus ground

Parameter	DMSP – Bihar: Before bias correction	DMSP – Bihar: After bias correction	DMSP – Odisha: Before bias correction	DMSP – Odisha: After bias correction
Terrain type	Plain	Plain	Plain	Plain
Reference	35 BMs	14 BMs as checkpoints	113 TBMs	48 BMs as checkpoints
Difference range (m)	–0.4 to 2.3	0.03 to 0.35	–0.3 to 3.1	0.01 to 0.29
Difference average (m)	1.32	0.12	1.58	0.09

corrected GOCE geoid, orthometric heights were derived and validated with checkpoints.

In the Kosi river basin, Bihar, 49 primary BMs were used for which ellipsoidal and orthometric heights were known. Out of these points, 35 BMs were used for comparison, bias estimation and the remaining 14 BMs were used as checkpoints for validation. Geoidal undulation value at each point was calculated using eq. (1). At the same points, GOCE geoidal undulations were also computed. These undulations were plotted and comparison was made (Figure 2). A systematic offset in the GOCE geoidal undulation was observed in comparison with ground data. The bias was estimated to be 1.3 m. The small kinks and dips present in ground geoid are due to the better resolution of ground data in comparison with GOCE geoid. As the pattern was found to match ground data, a simple bias of the order of 1.3 m was applied on the GOCE data and plotted. The linear trend of both the datasets implies that field and GOCE geoid undulations are well overlaid. All the ellipsoidal heights in the study area were converted into orthometric heights using bias-corrected GOCE geoid and eq. (1) and compared with 15 independent BMs. The results show that the difference was brought down to 12 cm. In the Mahanadi river basin, Odisha, totally 161 orthometric height points comprising BMs and TBMs were used. Out of this, 113 TBMs were used for comparison and estimation of bias and the remaining 48 BMs were used for validation. The same exercise was repeated similar to Bihar (Figure 3). The pattern and results were similar. Here the results show that the difference was brought down to 9 cm. The summary of geoidal undulation difference and bias-corrected results for both study areas is presented in Table 1.

From Table 1, it is evident that bias-corrected geoid from GOCE introduces 10 cm error in orthometric height. An additional 15 cm error is introduced (due to orbit, attitude and photogrammetric processing) during the processing of airborne digital camera/LiDAR. Hence by

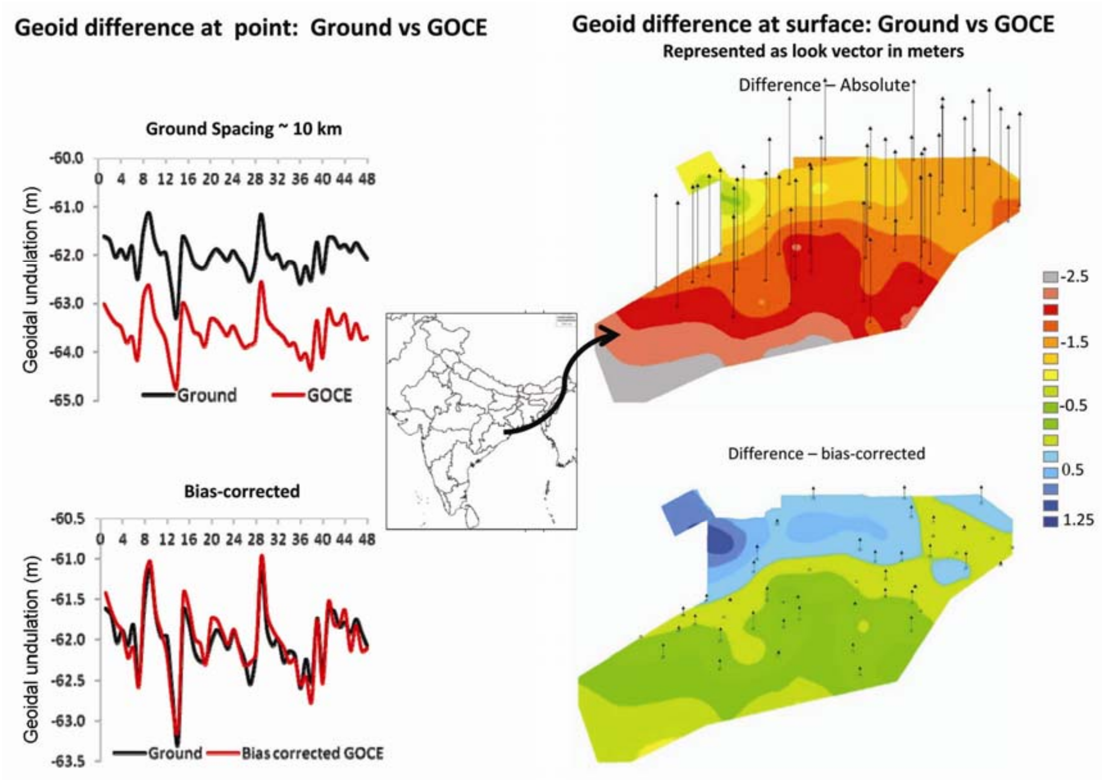

Figure 3. Difference between GOCE and ground data – absolute versus post bias correction of Mahanadi river basin, Odisha.

including both the sources of error, high-resolution DTM can be generated with vertical accuracy better than 25 cm. From the results of two study areas, it is observed that bias is same with BMs or TBMs, and hence there is no need to establish TBMs by extensive ground levelling, thereby saving time and cost.

Researchers will be able to use the full potential of GOCE geoid for the generation of high-resolution DTM with reference to orthometric height. As there is a fixed bias present between GOCE and ground, one can easily calibrate GOCE data so that accurate geoid model is available for the generation of high-resolution DTM. Establishment of more TBMs by ground levelling in the study area can be completely avoided, thereby saving time and cost. However, if primary BMs are not available in the project area, one needs to traverse to the project area from the known BMs by ground levelling and calibrate the GOCE data.

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