A comparative evaluation of the gravity signatures over a part of the western Indian offshore for lithospheric studies

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Three different satellite gravity data e.g. Hwang gravity (High Resolution), GRACE gravity and ERS-1 gravity over the Bombay High region in the western Indian offshore were examined in the present study. Hwang gravity data has been found most suitable for exploration in the offshore region and for lithospheric studies, apart from utilization of non-altimetric source of satellite gravity e.g. GRACE data and ERS-1 altimeter-derived gravity. Further, 2D/3D image generations and enhancement from high resolution gravity data have been found useful for delineation of Bombay High structures which is highly prospective for oil exploration. In addition, the major trends found in the western offshore are NW-SE, NNW-SSE and E-W as observed using 3 × 3 left diagonal edge detection technique over the gravity anomaly image.

Keywords: Free-air gravity, Indian offshore, Bombay High, High resolution satellite gravity, GRACE, ERS-1, Power spectral density.

Introduction
Satellite altimetry offers to act as an inexpensive and rapid reconnaissance tool for the sparsely surveyed Indian Ocean region. It can as well be used to infer subsurface geological structures analogous to gravity anomaly maps generated through ship-borne survey1. Presently available dense satellite altimeter data with ~ 4 km off-track resolution makes a detail recovery of the marine gravity field which can be used for more detail geological exploration of the sea floor. With advent of high resolution altimeters like GEOSAT - Geodetic Mission (GM) it has now become possible to obtain more details for the offshore exploration. With compilation of multiple radar altimeters e.g. ERS-1/2, GEOSAT GM, TOPEX/POSEIDON and Seasat, the high resolution data could be generated, which gives more valuable information of the offshore region. A number of known megastructures e.g. Bombay High, Saurashtra platform, Carlsberg ridge, 85°E ridge, Ninetyeast ridge, etc. could be precisely identified and successfully interpreted with the help of such high resolution altimeter data over the Indian offshore region2. Some of the anomalous zones (basins near Mangalore and off Bombay High in the western offshore and Krishna-Godavari basin, Palar basin off Madras coast in the eastern offshore) have been identified as potential sites for occurrences of hydrocarbon-bearing structures2. The Carlsberg ridge, the Bombay High region and the Andaman trench patterns could be more precisely identified using high resolution satellite gravity data which has helped to delineate the detailed transform faults and fracture zones in this region3,4.

GRACE (Gravity Recovery And Climate Experiment) launched in 17 March 2002, from Russia carrying the two GRACE satellites into orbit. The twin GRACE satellites- Tom and Jerry – orbit the earth 16 times a day at an altitude of 311 miles. Separated by 137 miles (220 km), a precise microwave ranging system constantly measures the distance between them to within the equivalent of 1/10th the width of a human hair. That ability, coupled with Global Positioning System technology, permits scientists on the ground to monitor changes in the distance between them to within the equivalent of 1/10th the width of a human hair. That ability, coupled with Global Positioning System technology, permits scientists on the ground to monitor changes in the speed and distance between the German-built spacecraft. Those changes indicate differences in the mass of the Earth’s surface below and corresponding variations in its gravitational pull. As they travel above different parts of the Earth, the varying gravitational pull alters the distance between them slightly. There is a delay between the two satellites cross over the same path; the satellites move closer and further apart from each other. By measuring their
changing speed, the gravitational force required to cause those changes in motions can be calculated. Because the satellites travel over same areas repeatedly, the changes in gravity are observed from one month to the next. More information about GRACE is available in website: http://www.csr.utexas.edu/grace.

Main objectives of this study are: i) To generate and compare high resolution, GRACE and medium resolution ERS-1-derived gravity maps/data over the Bombay High; and ii) to explore the utilization of high resolution gravity over a part of the western offshore. With ERS-1 168 day repeat altimeter data for period of one year, a database had been generated earlier across the Indian offshore regions with cross track resolution as high as 16 km. However, with the availability of high resolution Geosat GM (Geodetic Mission) data along with Seasat, ERS-1/2 and TOPEX/POSEIDON altimeter data, it is now possible to generate a high resolution gravity data with a grid of around 4 km × 4 km. GRACE gravity data has been downloaded from website: http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html.

Materials and Methods

The study area of the intensive test site is the prime oil-producing basin, the Bombay High of India, with latitude and longitude limits of 18-22° N and 70-72° E respectively, considering the unavailability of ship data in the public domain due to presence of Oil and Natural Gas Corporation (ONGC) platform, which has been used to interpret the different satellite-derived (gravity anomaly) data quality for proper geological interpretation of megastructures (Fig. 1). Later, a major part of the western offshore has been taken up for geological interpretation.

The brief methodology for generation of these three databases is as follows:

Generation of ERS-1 (168 day repeat) database

The sea surface height (SSH) with reference to the ellipsoid is computed after applying corrections due to instrumental bias and atmospheric propagation delays. It is a fundamental geophysical parameter used for various oceanographic and geophysical studies.

\[
\text{Sea surface height (SSH)} = \text{Orbit height (H)} - \text{Corrected altimetric range (h')} \quad \ldots \quad (1)
\]

The SSH observed by the altimeter is only an instantaneous sea surface and deviations of SSH from the geoid are due to various dynamic variabilities e.g. ocean tide, solid tide, electromagnetic bias, inverse barometric pressure effect, etc. Correction of SSH for dynamic variabilities yields mean sea surface height (MSH). The difference of MSH from the classical geoid is the dynamic sea surface topography (SST) which is due to currents, eddies etc. The dynamic sea surface topography part in the MSH is minimized by taking average of repeat observations over a period of time. Generalized procedure used in computation of residual geoid and gravity anomaly using altimeter data is given in Majumdar et al. The contributions due to mass distribution within the lithosphere are manifested in the form of medium and long-wavelength components (<1000 km). The deeper earth effect has been removed by spherical harmonic modeling of the geopotential field. Rapp's geoid model expanded up to a degree and order 50 has been used to remove the long-wavelength component, caused by the masses at deeper depth below the earth. Residual geoid is obtained after removing the deeper earth effects from classical geoid, which contains information due to bathymetry as well as lithospheric anomalies.
Gravity anomaly modeling using geoid

Fast Fourier Transform (FFT) approach uses geoid for computation of free-air gravity anomaly\textsuperscript{11}. FFT approach is based on a flat earth approximation and is derived from the two fundamental equations, namely the Brun’s equation and the equation of Physical Geodesy\textsuperscript{12,13}. The relation between gravity anomaly and geoid undulation derived from the above two fundamental equations were given by Chapman\textsuperscript{11}:

$$\text{F} (\Delta g) = g_\circ |k| \text{F}(N) \ldots \ldots \text{(2)}$$

where, $\text{F} (\Delta g) =$ Fourier transform of free-air gravity anomaly

$\text{F} (N) =$ Fourier transform of geoid undulation

$g_\circ =$ Normal gravity

$|k|$ = one-dimensional wave number associated with wavelength $\lambda$.

Generation of high resolution database

Hwang et al.\textsuperscript{6} have done a very detailed data assimilation using various altimeter data sets and Levitus topography for calculation of the deflection of the vertical and then generating $2 \times 2$ minutes (4 $\times$ 4 km) grid. Global mean sea surface heights (SSHs) and gravity anomalies on a $2' \times 2'$ grid were determined from Seasat, GEOSAT (Exact Repeat Mission and Geodetic Mission), ERS-1 (1.5-year mean of 35-day repeat and geodetic Mission) TOPEX/POSEIDON (T/P) (5.6-year mean) and ERS-2 (2-year mean) altimeter data over the region $0^\circ$–$360^\circ$ longitude and $-80^\circ$ to $+80^\circ$ latitude. To reduce ocean variabilities and data noises, SSHs from non-repeat missions were filtered by Gaussian filters of various wavelengths. A Levitus oceanic dynamic topography was subtracted from the altimeter-derived SSHs, and the resulting heights were used to compute along track deflection of the vertical (DOV). Geoidal heights and gravity anomalies were then computed from DOV using the deflection-geoid and inverse Vening Meinesz formulae. The Levitus oceanic dynamic topography was added back to the geoidal heights to obtain a preliminary sea surface grid. The difference between the T/P mean sea surface and the preliminary sea surface was computed on a grid by a minimum curvature method and then was added to the preliminary grid. Details of the methodology for obtaining high resolution geoid and gravity from altimeter-derived sea surface height have been discussed elsewhere\textsuperscript{2,6}.

Generation of GRACE gravity data

In this study we have used GRACE data generated from GRACE satellite mission archives, processed for two years gravity field using EIGEN-GL04C equation (2006) and at grid interval of 0.01° $\times$ 0.01° for the study area. Combined gravity field Model E16EN-GL04C complete to degree and order 360 was released on march 31, 2006. This model is a combination of GRACE and LAGEOS mission plus 0.5° $\times$ 0.5° degrees gravimetry and altimetry surface data and is complete to degree and order 360 in terms of spherical harmonic coefficients. High resolution combination gravity models are essential for the static gravity potential and its gradients are needed in the medium and short wavelength spectrum. Typical examples are precise orbit determination of geodetic and altimetric satellites or the study of the Earth's crust and mantle mass distribution. The ocean dynamic topography and the derived geostrophic surface currents both derived from altimeter measurements and an oceanic geoid, would be strongly correlated with the mean sea surface height model used to derive terrestrial gravity data for the combination model.

Therefore, the satellite-only part of EIGEN-GL04C is provided here as EIGEN-GL04S1. The contributing GRACE and LAGEOS data are already described in the EIGEN-GL04C description. The satellite-only model has been derived from EIGEN-GL04C by reduction of the terrestrial normal equation system and is complete up to degree and order 150 (GRACE website)\textsuperscript{7}.

Results and Discussion

Three different satellite gravity images generated from three gravity databases as described above over the study area are shown in Fig. 2: (a) Hwang: high resolution; (b) GRACE; (c) ERS-1 medium resolution data. Later, a profile AB has been drawn across Bombay High (A: 70.03°E, 18.06°N; B: 71.65°E, 19.88°N) using different gravity data as plotted in Figs 3 a-c. As it can be seen from Figs. 3 a-c, geological features including the continental shelf, the slope region, the Bombay High etc. could be sharply delineated using high resolution gravity data and then satisfactorily using GRACE gravity data. However, they are quite much blurred in medium resolution data. Later, 3D Gravity over the Bombay High has been generated using high resolution gravity data (Fig. 4), which has been found useful for delineation of the Bombay High structures, which is highly prospective for oil exploration\textsuperscript{14-16}. 

$$F (\Delta g) = g_\circ |k| F(N) \ldots \ldots \text{(2)}$$
Fig. 2—Satellite gravity images generated from gravity database over the study area (a) Hwang; (b) GRACE; and (c) ERS-1.

Fig. 3—Free-air gravity profile along AB (A; 70.03°E, 18.06°N; B; 71.65°E, 19.88°N) as generated from a) HR data; b) GRACE data; c) ERS-1 data.
Different power spectral densities have been generated using ship, ERS-1 and high resolution (HR) satellite-derived gravity data and compared for a longitudinal profile over the Bombay High across 71° E (Lat. 19° N - 20° N). The high resolution data has shown high resemblance with ship data compared to that of ERS-1 data (Chatterjee et al. — refer Fig. 13).

After confirming the quality of high resolution (HR) gravity data, the same has been used to generate the free-air gravity image over a part of the western offshore and a number of existing features including Bombay High, Continental Shelf, Margin, few seamounts etc. could be delineated with clarity (Fig. 5). Later a 3 x 3 left diagonal edge detection filter has been applied over the gravity image. A good number of additional features including lineament, faults, boundary of major existing features including Laxmi ridge and basin, Bombay High, few seamounts etc. could be distinctly delineated, in addition to a pseudo-three-dimensional visualization of geological/geomorphological features (Fig. 6). A good number of faults could be delineated over the Bombay High, which may have far reaching consequences for hydrocarbon exploration in this region.

The major linears as well as continental margins and other major features which were found using 3 x 3 left diagonal edge detection technique over the gravity anomaly image have also been marked. However, there may be some other linears, which have been missed/overlooked in the image generated by this technique. Major linears were earlier detected over the Indian offshore using visual interpretation of the generated free-air gravity image (Majumdar et al. 1998) and the major trends observed were NE-SW, NW-SE, N-S, E-W and ENE-WSW. In the present case, the major trends found in the western offshore are NW-SE, NNW-SSE and E-W. However, few NE-SW trend lines could be observed in Fig. 5 as well. It is unlikely to have ‘flight line bias’ (rather ascending/descending trends bias) in satellite-derived gravity anomaly images after several corrections incorporated. However, the western continental
margin had been separated/detached in the geological time from Gondwanaland/Madagascar with NW-SE trend, which may generate some sort of biasness along NW-SE. The bathymetry contours, continental margin, faults and other large scale features are predominant along NW-SE.

Conclusions

Comparison of high resolution satellite gravity with ERS-1 and GRACE gravity over the Bombay High region shows that high resolution gravity delineates the geological features more sharply. Similarly, 3D image generated from high resolution data has been found useful for delineation of the Bombay High structures, which is highly prospective for oil exploration. Free-air gravity image generated over a part of the western offshore and its enhanced image as generated using high resolution (HR) data have generated a number of geological/geomorphological features; some of which may have an impact on hydrocarbon exploration in this region. In the western offshore, the major trends found are NW-SE, NNW-SSE and E-W as observed using 3 × 3 left diagonal edge detection technique over the gravity anomaly image. From all these results, it is clear that high resolution satellite derived free-air gravity has become a very useful tool for marine lithospheric studies and exploration of the ocean basins.

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