

## **STUDY OF SATELLITE GRAVITY OVER THE SUMATRAN EARTHQUAKE REGION**

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### **Abstract :**

The devastating earthquake (and the corresponding tsunami) that struck the Indian Ocean near Sumatra (Indonesia) on 26 December, 2004 was extremely powerful. In the present study, a very high resolution 3D gravity image has been generated over a part of eastern Indian offshore over the Sumatran earthquake region. Four latitudinal gravity profiles have been generated across the epicenter/aftershocks regions and down below. A drastic change of gravity anomaly patterns (~130 mGal) near the epicenter and the aftershocks regions could be observed, which is however slowly diminishing as one goes away from the epicenter. It is expected that the large changes in gravitational values near the subduction zones may cause severe disturbances leading to the plate motions where as minor/major gravitational differences in other areas may be due to the changes in densities of different lithospheric zones/sedimentary layers beneath that area in a comparatively isostatically equilibrium region.

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## 1. Introduction

The devastating earthquake that struck the Indian Ocean near Sumatra (Indonesia) on 26<sup>th</sup> December, 2004 was extremely powerful. It has already been the focus of discussions in the prime newspapers/scientific journals and in news headlines all over the world as the devastation by the earthquake and the corresponding tsunami have caused immense damages to a number of countries including Indonesia, Sri Lanka and India. The devastating earthquake has accelerated the Earth's rotation. Geophysicists have estimated that the shockwave shortened the period of our planet's rotation by some three microseconds. The change was caused by a shift of mass towards the planet's centre, as the Indian Ocean's heavy tectonic plate lurched underneath Indonesia's one, say researchers at NASA's Jet Propulsion Laboratory in Pasadena, California. This caused the globe to rotate faster. NASA has estimated that Earth now tilts by an extra 2.5 centimeters in the wake of the jolt (Hopkin, 2004).

TOPEX/Poseidon and Jason - 1 satellite altimeters passed over the Bay of Bengal two hours after the massive earthquake and captured the only measurements of the corresponding tsunami's height in deep waters. The satellites saw the first two wavefronts by the main quake, spaced 500 to 800 kms apart. These reached a maximum height of 50 cms. in the open ocean (New Scientists, 2005).

The Indian Ocean has experienced, along with three main phases of seafloor spreading, two major plate

reorganizations from the late Jurassic to the present. The first phase of spreading started in northwest-southeast direction and resulted in India's movement away from Antarctic-Australia during the early Cretaceous. During the middle Cretaceous, it appears that the Indian plate rotated from its early NW-SE to N-S direction and moved at a slow spreading rate. The second phase of spreading started in the north-south direction and during this period, India drifted in north-south direction from Antarctica with a rapid speed of 11 to 7 cm/yr. The Indian and Australian plates merged and formed as a single Indo-Australian plate during the middle Eocene. The third phase of spreading initiated in northeast-southeast direction, and appears to continue since then. Also, ridge jumps occur as tectonic events and create more complexity to the evolution of ocean floor besides plate reorganizations (Bhattacharya and Chaubey, 2001; Ramana et al., 2001).

Satellite altimetry has recently emerged as an efficient alternative for expensive and hazardous ship-borne gravity survey (Stewart, 1985). The averaged Sea Surface Height (SSH) as obtained from satellite altimeter is a good approximation to the classical geoid, which contains information regarding mass distribution in the entire earth. The underlying concept of the 'Satellite Gravity Method' is that the sea surface height (SSH) measured by satellite altimeter when corrected for dynamic variabilities due to tides, waves, eddies etc. corresponds to mass distribution below the earth (Fu et al., 1988; Lundgren and Nordin, 1988;

Majumdar et al., 2001). Value-Added Products (VAP) in the form of different wavelengths residual/prospecting geoid and gravity have been generated over the Indian offshore using Geosat (Geodetic Satellite, USA) GM, ERS-1/2 (European Remote Sensing Satellite), TOPEX/POSEIDON (USA/France) and Seasat (USA) altimeter data (Hwang et al., 2002; Majumdar and Bhattacharyya, 2004). Distinct clarities could be achieved in detailing the free-air gravity maps in 1:5 million scale using the present high resolution data (~3.33 km). In the present study, in addition to the development of methods and applications for satellite-derived geoid/gravity, an attempt has been made for study of the gravity signatures over the epicenter and aftershocks regions near Sumatra.

## 2. Objectives

Major objectives of the present study were to generate and study of very high resolution satellite gravity over the Sumatran earthquake region with reference to the severe earthquake on 26<sup>th</sup> Dec., 2004.

## 3. Data sources and the study area of interest

Geosat GM (Geodetic Mission), ERS-1/2, TOPEX/ POSEIDON and Seasat altimeter data have been used to generate this high resolution satellite gravity over the area of interest (Hwang et al., 2002). Because of being very high density in nature (off-track resolution ~ 3.33 km), sea surface parameters as well as gravity derived from these data are more accurate and detailed. The study

area of interest is Bay of Bengal/northeastern Indian ocean, in general, and the Andaman and Sunda trench systems, in particular (Lat. 0-22 °N, Long. 87-100 °E).

## 4. Methodology

Details of the methodology for obtaining geoid and gravity from altimeter-derived sea surface height have been discussed elsewhere (Rapp, 1983; Sandwell and Smith, 1997; Majumdar et al., 2001; Hwang et al., 2002; Majumdar and Bhattacharyya, 2004).

The geoidal undulation obtained after removing the contributions due to bathymetry and deeper earth is known as prospecting geoid which corresponds to the mass distribution in the lithosphere (Lundgren and Nordin, 1988). An anomaly (a high or a low) in the geoid may be due to i) a bathymetric feature e.g. a sea mount, trench, ridge etc, ii) a lateral density variation in the lithospheric zone, iii) an anomaly deep-seated inside the earth *i.e.* below the lithospheric zone, or iv) any combination of the above three features. For extraction of geological features/identification of shallow focus earthquakes in the oceans, which are more devastating, lateral density variations in the lithosphere is useful.

**4.1 Gravity anomaly modelling using geoid:** It is necessary to derive gravity anomaly from geoid, since the later is a traditionally accepted tool in oil/minerals exploration/oceanic processes studies. Fast Fourier Transform (FFT) approach uses geoid for computation of free-air gravity anomaly (Chapman, 1979). 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 (Moritz, 1980).

## 5. Results and Discussions

Geotectonic and gravimetric geoids over the Bay of Bengal have been discussed in details by several authors (Kahle, 1973; Curray et al., 1982; Subramaniam and Verma, 1992). The residual geoid undulation were extracted from the observed geoid undulation after removing the deeper earth effects (Majumdar et al., 2001). The average sediment thickness in the North-Eastern Bay of Bengal have reported 18-22 km. (Curray et al., 1982) In such high sediment thickness areas the residual geoid anomaly is more effective compared to the free-air gravity anomaly for mapping the basement undulations. In addition, the isostatic geoidal anomalies are defined as the dipole moment of vertical density distribution of the subsurface lithospheric features. Hence the residual geoid and the related free-air gravity can be utilized for interpretation of lithospheric undulations. The high geoidal undulations along the trench wall, and the close proximity of the aseismic 90°E ridge in the northern region, suggest the existence of Ninetyeast ridge as a hindrance to the overall subduction processes (Cloetingh and Wortel, 1985; Majumdar et al., 2001; Rajesh and Majumdar, 2004). The presence of this ridge up to 10°N was earlier reported by Ramana et al. (2001) by marine magnetic studies of the region.

The geoidal anomalies also are converted to free-air gravity anomalies which are particularly useful in the deep

sea where traditional ship-borne geophysical data are either unavailable or scanty. In the eastern offshore regions of India, regional crustal features, e. g. the 85°E ridge, the Central Basin, the 90°E ridge, the Sunda Arc and the Andaman shelf, etc. have been well defined from satellite-derived geoid/gravity anomaly patterns and have been verified with related ship-borne geophysical survey data (Majumdar et al., 2001). Generalized free-air gravity contour patterns in the eastern offshore show the values between 0 to -5 mGal, which may be due to near compensated lithospheric features in those regions (Curray et al., 1982; Subramaniam and Verma, 1992; Rajesh and Majumdar, 2004).

A very high resolution 3D gravity image has been generated over a part of eastern Indian offshore containing Ninety East Ridge, Andaman subduction Zone, Sumatra etc. (Fig. 1).

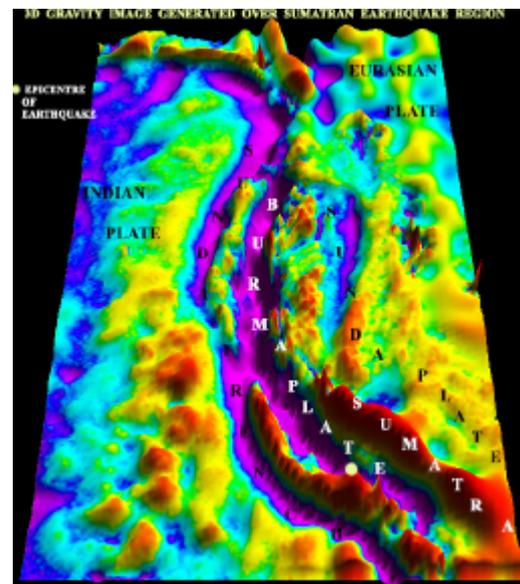


Figure 1: 3D satellite gravity over Sumatran earthquake and its surroundings

This high resolution two-dimensional satellite gravity image has been superimposed over the earthquake occurrence map of 26<sup>th</sup> Dec., 2004 near Sumatra (Fig. 2).

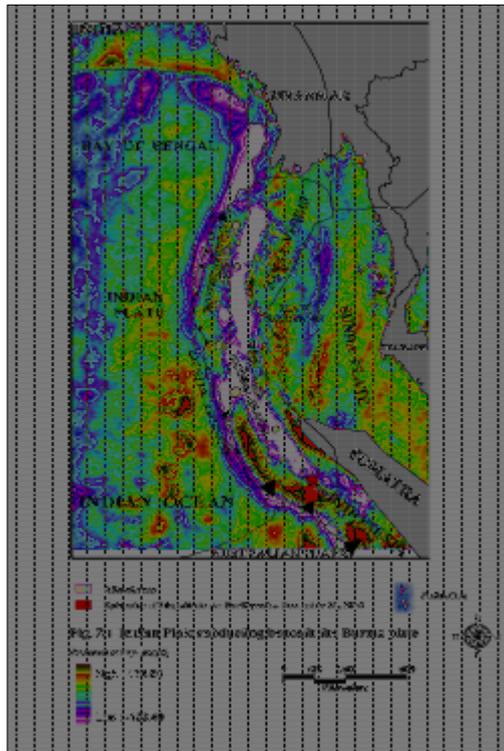
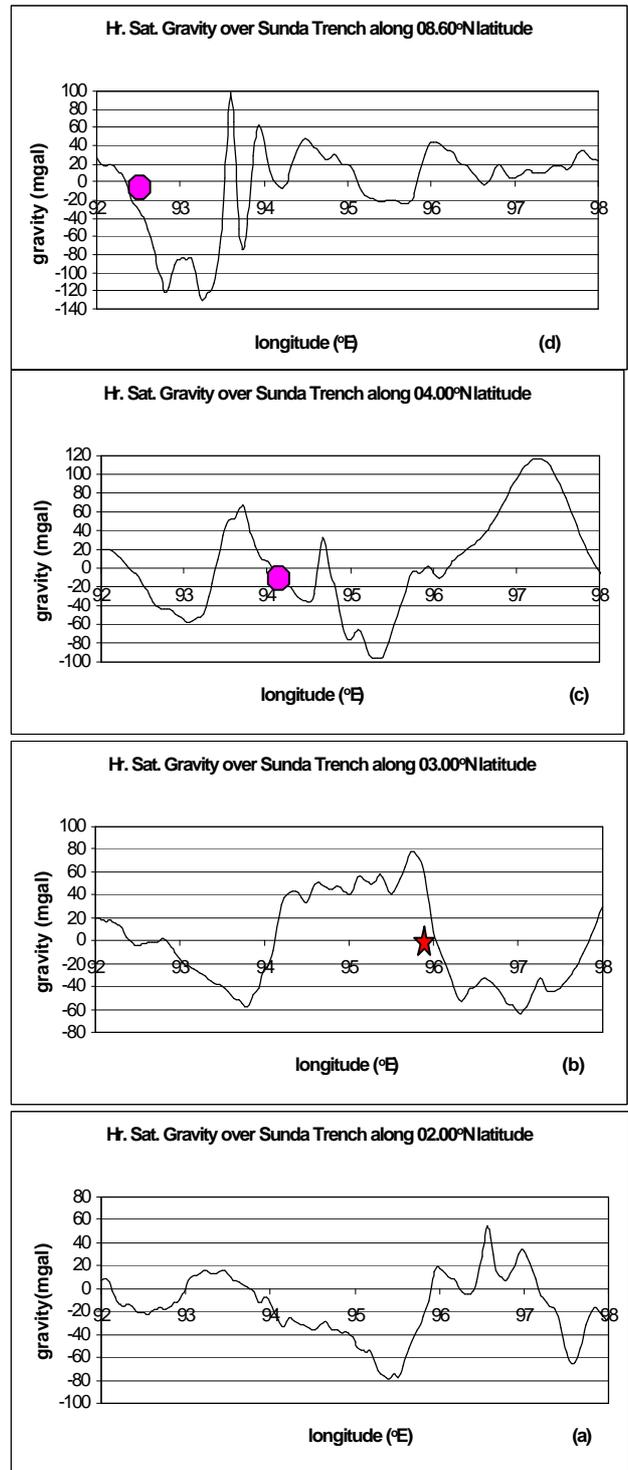


Figure 2 : Satellite gravity superimposed over the earthquake occurrence tectonic map

Four latitudinal ( $2^{\circ}$ ,  $3^{\circ}$ ,  $4^{\circ}$  N and  $8.6^{\circ}$  N) gravity profiles have been generated across the epicenter and the aftershocks regions and down below (Figs. 3 a – d). Comparison made has shown a drastic change of gravity anomaly patterns (as high as 130 mGal) near the epicenter and the aftershocks regions (Figs. 3 b, c, and d), which is however slowly diminishing as one goes away from the epicenter (Fig. 3 a). It has been observed that ridges are close to isostatic equilibrium but sinks are characterized by topographic trenches (e.g. Sunda Trench) which show the largest negative

gravity anomalies (Rajesh and Majumdar, 2004). This gravitational difference might have caused the plate motion leading to the severe earthquake (Mahapatra, 1987). It is expected that the



● Aftershock      ★ Epic. of Eqk.

Figures 3 (a-d): Latitudinal gravity profiles across epicenter, aftershocks regions and down below

large changes in gravitational values near the subduction zones may cause severe disturbances leading to the plate motions where as minor/major gravitational differences in other areas may be due to the changes in densities of different lithospheric zones/sedimentary layers beneath that area in a comparatively isostatically equilibrium region (Figs. 3 b, c, and d). Song and Simon (2003) have considered variations in the gravity field as a predictor of seismic behavior and have found that within subduction zones, the regions where one of the earth's plates slips below another, areas where the attraction due to gravity is relatively high are less likely to experience large earthquakes than areas where the gravitational force is relatively low. They have examined existing data from satellite-derived observations of the gravity field in subduction zones. Comparing variations in gravity along the trenches with earthquake data from two different catalogs going back 100 years, the team found that, within a given subduction zone, areas with negative gravity anomalies correlated with increased large earthquake activity. Hence, in subduction zones, areas under high stress are likely to have greater gravity and topography anomalies, and are also more likely to have earthquakes. Due to the prevailing security restrictions, lat./lon. coordinates have been omitted in some maps.

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