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Review Article

Gravity and Geodetic Studies in India: Historical Observations and Advances During the Past Decade

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Gravimetry and Geodesy deal with the mass distribution and transport in the dynamic Earth system and determination of Earth's shape and size. Since the 18th century, Indian scientists have been extensively contributing to the progress of Gravity and Geodetic studies. This article discusses the historical geodetic developments and summarizes the efforts that involve measurements and modelling of gravity and geodetic data in India over the past decade, using conventional land surveys to satellite observations. Historical obsevations, such as the Great Trigonometrical Survey during 1790-1850 for defining geodetic reference frame and gravity and geodetic observations in the Himalayan region (1830-1843) for hypothesising the concept of Isostasy, are phenomenal contributions made from studies in India. Recent studies are largely focused on understanding of subsurface mass distributions and mass variability due to different geophysical phenomenon, refining of geodectic datum, continental deformation and resource exploration.

Keywords: India; Gravity; Geodesy; Geoid; Datum

Introduction

The gravity and geodetic research worldwide has evolved as a scientific interface to facilitate the integration of satellite-based observations with the terrestrial measurements thereby making all earth observations interoperable.Both gravimetric and geodetic (using land, marine, borehole, airborne and satellite-based) studies have made tremendous progress during the past few decade and provided valuable insights with regard to the behaviour of spatio-temporal dynamics of the Earth (Tiwari, 2010). There has been an increased focus on precisely defining the local and regional geoid models worldwide due to their significance in the areas of applied geophysics and geodetic studies. Apart from the use of geoid in the engineering applications of surveying (geodesy), the detailed knowledge of geoid undulations at different wavelengths areused to infer the subsurface mass distributionsin the Earth (Li and Götze, 2001).

There are numerous studies on the interpretation of geoid in terms of mass anomalies at depth, tectonic forces, isostatic state of the oceanic lithosphere, Earth's rotation, total water storage and ocean circulation (e.g., Bowin, 2000). The gravitational potential decreases with distance from the surface of the Earth at a slower rate than the gravity, the geoidal variations tend to reflect deeper mass anomalies compared to the gravity anomalies (Hackney, 2004). The geoid anomalies thus provide information in terms of the subsurface mass distribution and dynamics of the Earth (Bowin, 2000; Vanicek and Christou, 1993; Featherstone, 1997).

The Indian geoscientific community, particularly during the post-independence era, has made significant scientific progress and achievements in tandem with the developments that took place worldwide in gravity and geodetic studies. These studies have led to several improvements in the Indian geodetic datum that was established in 19th century by the Survey of India (SOI), preparation of gravity anomaly maps using dense terrestrial gravity measurementsand the integration of satellite-based gravity data with ground-based observations for various applications by different organizations. This paper is intended to provide a brief

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overview of the historical development of the gravity and geodetic measurements in India with special emphasis on the recent studies/research work carried out by the Indian researchers in the allied areas of gravity and geodesy for various applications.

Brief History of Gravity Surveys in India

Gravity surveys in India were initiated in 1865 by J.P. Basevi and W.J. Heaviside, British Captains, using two brass pendulums provided on loan to Government of India by Royal Society of England for establishing about 30 gravity stations from Kanyakumari to Ladakh during 1865 to 1873 (Walker *et al.*, 1901). Subsequently, Sterneck's half-second pendulums (1902 to 1925) and Cambridge pendulums (1926 to 1939) were used to establish 564 pendulum stations by the SoI in the different parts of the country. The pendulum measurements were suspended on account of the World War II from 1939 to 1947. The First gravimeter used in India was Frost gravimeter in 1947. Afterward, different organizations have procured gravimeters for the geophysical exploration, educational and training purposes. The systematic surveys were started during 1950s by the dedicated geodesists and geophysicists and continued over the years to map the subcontinent of India covering the northern mountains, the peninsular plateau, Indo-Gangetic plains, dense forests, deserts and coastal regions. Data of about 3000 gravity stations including 564 pendulum stations recorded during 1902-1955, have been published by Gulatee (1956).

Precise determination of the height of the Mount Everest is one of the most celebrated achievements in the history of Indian gravity and geodesy. The National refence gravity station, tied with Potsdam gravity basewas established at SOI, Dehradun and a North-South calibration line was set up (Manghnani and Woollard, 1963). Hari Narain *et al.* (1964) examined the status of gravity work in the country and found that a considerable amount of available gravity data were mostly referred to the old pendulum stations of SOI, which had irreconcilable discrepancies. Further, the entire gravity data in the country was brought on to a common datum tied appropriately to the World Gravity Net andused for the geodetic and crustral studies in India. NGRI initiated a National Gravity Programme of preparation of regional gravity studies of India in 1964 which led to the publication of a series of gravity maps of India in 1975.

Gravity base network was established and the gravity values were published in different parts viz Part-I:-150 gravity bases in South India (Qureshy and Brahmam, 1969); Part-II:- 93 gravity bases in Northern and Western India (Qureshy and Warsi, 1972); Part-III:- 50 gravity bases in North India (Qureshy and Warsi, 1973);Part-IV:- 125 gravity bases in North Eastern India (Qureshy *et al.*, 1973) and Part-V:- 16 gravity bases in Central India (Subba Rao *et al.*, 1982).During these investigations, several of the SOI stations were reoccupied for standardization anda few new first order and secondary gravity bases were also established by various organisations(Murthy *et al.* 1976; Verma *et al.* 1979; Singh *et al.*, 1986 and Radhakrishna *et al.*, 1998). Regional gravity surveys carried out by GSI over the Deccan traps during 1964-1970 delineated two major lineaments, one along the west coast and other along the 21st parallel degree north of the Earth's equatorial plane (Kailasam *et al* ., 1972). A detailed gravity survey covering 1900 gravity measurements in the Singhbhum region was carried out, which revealed Bouguer anomalies ranging from +10 mGal in the eastern part to about -60 mGal over the Singhbum granite batholith (Verma *et al.*, 1984). Further, a large numberof gravity measurements are carried out under the National Gravity Programme by SOI. GSI launched National Geophysical Mapping (NGPM) programme during the 2002-2003 with an objective to generate gravity and magnetic responses in potential areas of mineral exploration.

Gravity Map Series of India

In the year 1975, the voluminous gravity data at National Geophysical Research Institute (NGRI), Survey of India (SOI), Oil and Natural Gas Commission (ONGC) and the Hawaii Institute of Geophysics (HIG) were compiled and the first ever Gravity Map series of India (1975), with 10 m Gal contour interval was published on 1:5 million scale. These maps were based on 30000 gravity stations located along the major roads at intervals of 6-8 km, where benchmarks or spot heights were readily available.In case of geodetic data gaps, two altimeters were simultaneously operated to obtain elevations of the gravity stations. Taking into account all the factors that contribute to errors in the Bouguer anomaly values, the anomalies could be accurate within ± 1.5 mGal. In case of the Himalayan region, however, such accuracy could not be obtained for stations for which the elevations were acquired using altimeters. This set of maps - Bouguer Gravity, Free-Air and Isostatic anomaly maps, led to formulate new exploration activities in India besides someimportant basic research such as refining the ideas of isostasy. The relationship between gravity anomalies and elevation was empirically derived and used to predict the thickness of the crust. These maps are further upgraded as Gravity Map of India (2006; Fig. 1(A)), a collaborative effort of several organisations; NGRI, Geological Survey of India (GSI), Oil and Natural Gas Commission (ONGC), Oil India Limited (OIL) and Survey of India (SOI). Data from 51,356 gravity stations at 3 arc interval are included with the implementation of detailed terrain corrections to the gravity stations, new theoretical gravity formula based on the Geodetic Reference System 1980 (GRS80) and the International Gravity Standardisation Net 1971 (IGSN71) datum. These revised maps are prodigious assset to the geosceince researchers and explorers. A brief description of the gravity anomaly map in relation to the geological features is given below.

Bouguer Gravity Anomaly Map

A mjor feature of this map is the predominance of negative Bouguer anomalies over the subcontinent reaching to value of -380 mGal over the Himalaya. A few pockets of positive Bouguer anomalies are observedon the west coast and reaching to a maximum value of +60 mGal near Bombay. The anomalies exhibit alignments/trends parallel to the major structural trends of the subcontinent such as the NNW-SSE Dharwarian trend of South India, NE-SW Eastern Ghat trend parallel to the east coast of South India, NE-SW Aravalli trend of North-Western India, ENE-WSW Satpura trend of Central India and the Himalayan trend. Besides these regional trends, there are several gravity ‘highs’ and ‘lows’ reflecting local geological features. The sediments of the Vindhyan and Gondwana basins, sedimentary tracts of the east coast, intrusive granites of Peninsular India are all characterised by gravity ‘lows.’ Gravity ‘highs’ are observed over the Eastern Ghats, south-western Cuddapah basin, the Satpura and Aravalli ranges. In contrast, there are also areas where the Bouguer anomalies do not readily correlate with surface geology. Prominent among themare the ‘lows’ over the Deccan Traps of Western India, eastern Cuddapah basin, Peninsular gneisses of south India and Bastar region. The area west of Aravalli, which is mostly covered by alluvium, is a zone of mixed highs and lows. Synclinal structures filled with sedimentary or metasedimentary formations, volcanics, basic and ultrabasic intrusions, granitic intrusions of batholithic, differentiation of granites are inferred as gravity high in the Singhbhum group, Dhanjori and Simlipal basins in East India. The gravity high revealed in the North Eastern India, Shillong Plateauindicates the presence of relatively higher density underlying rocks. Strong negative anomalies as in Assam Valley, eastern Himalaya and Arakan-Yoma indicate areas characterized by mass deficiency due to a thickening of sediments and root formation or both. Gravity anomalies over India are used to construct crustal and lithospehric density models (e.g. Tiwari *et al.*, 2013).

Brief History of Geodetic Studies in India

Indian Horizontal Datum

The Indian Horizontal Datum adopted the Everest ellipsoid as the local geodetic datum in 1830. It is non-geocentric and the oldest among all the principal ellipsoids. The source of Everest ellipsoid set at Kalianpur with the initial point position of 24^0 07′ 11.26″N and 77^0 39′ 17.57″E. The center of the Everest ellipsoid does not coincide with the center of the Earth however, it is locally the best fitting ellipsoid to the Indian subcontinent. SOI generated topographical maps on 1:50,000 and 1:25,000 with reference to Everest ellipsoid for expressing geographical coordinates of places in India more than 150 years back. SOI has revised the ellipsoids from time to time (i.e., International (Hayford), GRS80 and WGS84) leading to the revision of the parameters assumed for the ellipsoid. Advancement satellite geodesy in satellite tracking technology has provided geodesists with new measurements such as VLBI, SLR, DORIS and GNSS to define the best Earth-fitting ellipsoid and for relating existing coordinate systems to the Earth’s center of mass. Accurate World Geodetic System (WGS84) ellipsoid was established using new gravity data, astro-geodetic measurements, satellite configuration and earth-fixed models (ECEF). WGS84 datum is a geocentric geodetic datum and globally consistent within + 1 meter, which does not change from place to place or from country to country.

Indian Vertical Datum

Vertical datum, which nearly coincides with mean sea level, provides the height information. In other words, the geoid is a visual representation of zero elevation which is considered to be reference height. This datum is derived based on tidal observations, astronomical, GNSS-levelling and gravimetric measurements. MSL is described as a tidal datum that is the arithmetic mean of hourly water elevations observed over a specific 19-year cycle (Aung *et al*., 2009). SOI has been using the astrogeodetic geoid for the Indian vertical datum observations with respect to Everest ellipsoid since 1840 and using the first-order levelling Bench Marks (BM) measured in the early nineteen century (Fig. 1(B)). Fore and back levelling and invar staves instruments were used for measurements. The first vertical datum for India was establieshed based onadjustment of leveling network, which had included data collected from 1858 to 1909 and referenced to MSL values of nine tide gauge stations and limited number of surface gravity observations.

Significant Contributions in Gravity and Geodetic Research During the Past Decade in India

Salient Outcome of the Geodetic Research

Everest datum, which was developed using a small volume of data, is not suitable for high precision geodetic and allied activities of the modern age. Utilizing open source global products for positioning, the datum transformation from Everest coordinate system to geocentric coordinate system (ITRF) was initiated in the 21st century (Singh, 2010). SOI has set up a Ground Control Point (GCP) Library, as a part of which 292 primary control points were established at a spacing of 250-300 km in the first phase. In the second phase,the network was strengthened with 2200 GCP Library pillars with an interval of about 30-40 km and in the third phase, further 65,000 GCP of 6-7 km spacing were added to provide necessary horizontal reference points. SOI completed the high precision levelling network with an adjustment of 45,775 km along the national and state highways, as a part of redefining Indian vertical datum project (Fig. 1(C)).

Nagarajan and Singh (2010) demonstrated the utilisation of GPS to provide planimetric coordinates of GCP's with 1 m control interval for initiating a comprehensive development plan for the Bangalore metropolitan area. GPS vertical datum has turned out to be a progressive tool in establishing a vertical network for engineering applications, though it has certain limitations. In the recent years, most of GTS benchmarks got destroyed due to urbanisation and industrial development. There are global gravity models that allow determining geoidal undulations; however, the global models are constrained by spatial resolutions. Determination of geoid undulations over southern Indian region is of specific importance because the largest geoid depression in the world is centered in the Indian Ocean encompassing South India (Marsh, 1979) and therefore a large spatial gradient of geoid undulation is observed in this region. Geoid height decreasing towards south reaching up to the minimum value of –106 m, located in the Indian Ocean, is generally known as Indian Ocean Geoidal Low (IOGL). The cause of this anomaly is attributed to the depression in the Core-Mantle boundary, relict of earlier subduction and so on. The wavelet analysis of the corresponding gravity low in the IOGL provides depth at ~1260 and ~693 km reported by Tiwari and Goyal (2010). Modeling of the large wavelength regional gravity anomaly corresponding to the IOGL provides a three-layer model at depths of 1300, 700 and 340 km (Mishra and Ravikumar, 2012) related to the spectral depths obtained from the geoid and regional gravity data with negative density contrasts. The relatively short wavelength sources of the spectrum of the geoid data at depths of 162 and 85 km suggest sources along the lithosphere-asthenosphere boundary (LAB) under the Indian continent and surrounding oceans, respectively. All the studies of this long wavelength geoidal low suggest a deep causative source, a density heterogeneities in the mantle. Upper to middle mantle low-density anomalies are mainly responsible for the formation of IOGL and are clearly explained by the presence of low-density anomalies in the ~300-900 km depth beneath the IOGL (Ghosh *et al*., 2017). Some of the recent studies attempted to compute an accurate geoid model without terrestrial gravity observations. Goyal *et al*. (2018) have shown that the EGM2008 model is the best GGM available for India with an accuracy of 28 cm, without model fitting. Similarly, GOCE GGM has demonstrated

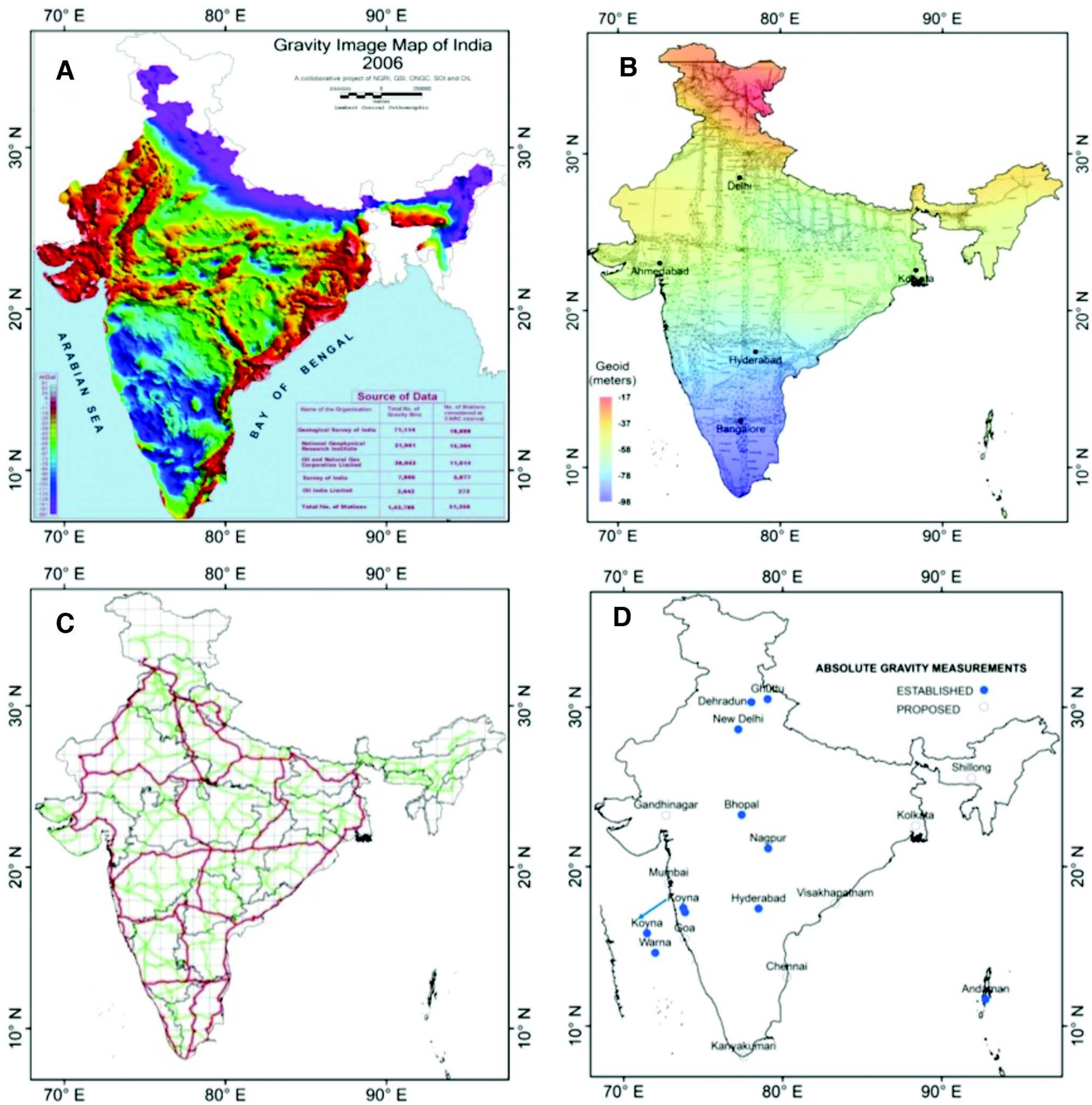

Fig. 1: (A) Bouguer gravity anomaly map of India :Gravity Map Series of India-2006; (B) Spatial distribution of GTS benchmarks in India (1905) (source: Wikipedia); (C) Status of high precision levelling (after Singh and Srivastava (2018)) and (D) Locations of established/proposed precise gravity reference stations in India using the absolute gravimeter

significantly better results with an accuracy of 19 cm for India after modelling with seven parameterisations. SOI developed the first version of Indian Geoid model called INDGEOID ver 1.0 in 250th year celebrations of Surveying and Mapping activities in India in 2017.

Local Geoid Determination

Orthometric height is the height of the surface above or below the geoid. Precise information of geoid undulation is vital for understanding the subsurface mass distribution of the Earth. The geoid surface is not an actual physical figure of the Earth, thus it cannot be directly measured. The current point-based geodetic height determined using GPS-levelling is not sufficient to generate the accurate geoid surfacefor any application. The determination of orthometric heights over a local area is obtained through the GPS-levelling observations or calculated from terrestrial gravity values. Few attempts were made for computation of gravimetric geoid and the results were compared with GPS-levelling measurements over the Indian subcontinent (Singh *et al*., 2007; Carrion *et al*., 2009; Srinivas *et al*., 2012; Singh and Srivastava, 2018). Ghosh and Mishra (2016) determined the geoid undulation for Dehradun using the astro-geodetic method in conjunction with GNSS observations. The accuracy of the computed geoid has been found to be better than global geoid models. Mishra and Ghosh (2017) computed accurate geometrical geoid model in Dehradun with the help of sufficiently dense and homogeneous control stations. The advantage of the geometrical approach of geoid modelling is its being non-dependence on gravity field or deflection of vertical. Utilization of existing gravimetric data may provide the precise geoid surface with the help of different geoid computational methods such as Remove Compute Restore (RCR) method, Stokes-Helmert method, Least squares modification of Stokes formula etc. SOI derived the optimised solutions of the local gravimetric geoid with Free Air gravity anomaly data for some region of the Indian subcontinent by implementing the RCR method. GPS-Levelling Points: 84 (Bangalore city: Singh *et al*., 2006), 50 (Delhi region: Singh *et al*., 2007) and 72 (Central India: Singh, 2007) were selected for performing a realistic assessment of geoid model and subsequently optimised the integral parameters of Stokes Formula. The RCR procedure has been applied to combine the GGM, high-frequency height data from a DEM and local terrestrial gravity anomaly data. The hybrid geoid model has shown a considerable improvement over gravimetric geoid, and standard deviation of post-fitting residuals is improved to approximately 5cm precision after the Least Square Collocation (LSC) technique.

Carrion *et al*. (2009) computed the geoid undulations over a part of southern Indian region with terrestrial gravity data using the RCR technique to calculate Stokes coefficients and compared with EGM2008 global geoid model with a difference of fewer than two meters. Similarly, Prajapati and Singh (2010) determined the residual geoid for some of the Indian plateaus (i.e., Saurashtra, Malwa, Satpura, Ajanta) by removing the effects of geopotential model, Free-air gravity anomalies and height data by applying the LSC technique. The geoidal undulations suggest that the primary source of geoidal high lies within the crust-upper mantle. Another attempt is made to compute and validate the geoid undulations (Fig. 2) concurrently using terrestrial gravity data and GPS-levelling observations and to compare them with geoid undulations obtained from global geopotential models over the southern part of India (Srinivas *et al*., 2012). An agreement between GPS-levelling data and global geopotential model was found on a regional scale. However, geoid from GPS-levelling over a small region is considerably adequate to the gravimetric geoid and suitable for the local applications.

Geoid undulations are also derived from LiDAR survey and GTS benchmarks over the Kosi and Mahanadi basins and compared with the GOCE derived geoid heights. A bias of 1.5 m with reference to the ground geoid is reported by Satishkumar *et al*. (2014). The hybrid geoid is a combination of the Geometric geoid and Gravimetric geoid. Tripathi and Tripathi, (2015), utilised the terrestrial gravity, elevation and positioned data of 190 GPS-Levelling data spread across Chhattisgarh region to calculate the hybrid geoid with an accuracy of 60 cm. Mishra and Ghosh (2016) also adopted the RCR method to determine gravimetric geoid for two different types of topographical regions (i.e., Hyderabad and Dehradun) and achieved ~ 20 cm accuracy in the highly elevated Himalayan region and ~ 10 cm in the gentle elevated Hyderabad region.Singh and Srivastava (2018) explained the development of Gravimetric geoid model for Western India using the RCR method and implemented the spherical Fast Fourier Transformation (FFT) with optimised Stokes's kernel to achieve an accuracy of 14 cm for gravimetric geoid and 7 cm for hybrid geoid model with the help of GNSS observations on first order benchmarks at 39 locations. SOI initiated a program "Redefinition of Indian Vertical Datum" by optimal utilisation of existing gravity GNSS and levelling data to develop a hybrid geoid model, to achieve an accuracy of better than 10 cm.

High Precision Gravity Measurements

The absolute gravity (AG) observations across India and at Maitri, Antarctica were first carried out by NGRI, to establish reference gravity stations with aprecision of 1 μGal using Micro-g LaCoste FG5 absolute gravimeter. A reference gravity base station was established with an accuracy of about 2-3 μGal with the help of Absolute Gravimeter (FG5 #219) at

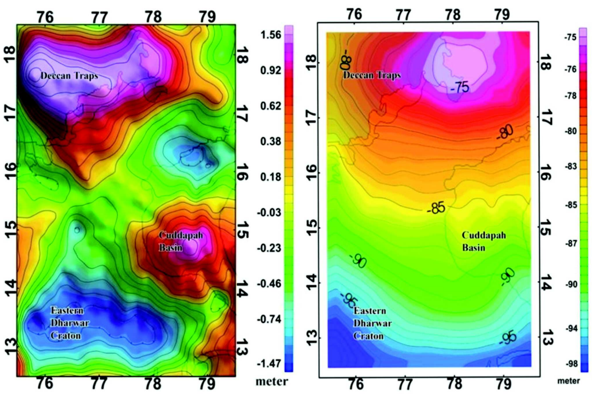

Fig. 2: Residual geoid and gravimetric geoid of a part of south India (after Srinivas *et al.*, 2012)

the NGRI Gravity Observatory, Hyderabad (Tiwari *et al.*, 2006b). New precise reference gravity base stations were established in different parts of India (New Delhi, Dehradun, Ghuttu, Bhopal, Nagpur, Koyna, Warna, Port Blair and Maitri, Antarctica (Tiwari *et al.*, 2006b)). The AG observations comprised of regular repeat measurements over a network of existing and proposed absolute gravity sites (Fig. 1(D)) throughout India to provide information about the mass redistribution, vertical deformation and metrological applications (Tiwari *et al.*, 2014a).

The Superconducting Gravimeters (SG) are in operation at two locations in India, Ghuttu by WIHG, Dehradun (Arora *et al.*, 2008) and Badargadh by ISR, Ahmadabad. The SGs continue to provide a high precision record of the time variation of gravity with an accuracy of nGal. SG observations at both the above locations are located by other geophysical observations with the primary objective of earthquake precursory studies. Chauhan *et al.* (2016) observed the annual variations in SG gravity data at the rate of 112 nms^{-2}/year with a variation of 16 m in water table level and vertical displacement of 2.2 mm/year. Repeat AG observations are being madeat the site of SG located in the Himalayan region for drift corrections and calibration of SG. Gravity variations using gPhone gravimeter are being continuously recorded at Warna, Maharashtra, a seismically active region of peninsular India for investigation of potential gravity changes related to seismic activities. Prasad *et al.* (2017) successfully demonstrated the temporal gravity changes recorded by using gPhone and GRACE satellite and interpret the observed changes in conjunction with seismological, geodetic (cGPS) observations and groundwater level measurements.

Satellite Gravimetry

Most of the Indian researchers engaged in the observation and modelling of the earth's gravity field are focusing on deciphering tectonic and geodynamic processes that have shaped the present day lithospheric structure. The studies are carried out over the diverse tectonic and geological setting of the Indian subcontinent through a large number of gravity data in peninsular India. Since ground and marine gravity measurements cannot adequately cover the Indian subcontinent and adjoining ocean, satellite measurements are often oused. High-resolution Gravity field determination from space can be obtained from various measurement methods, namely Satellite radar altimetry (Geosat, European Remote Sensing (ERS-1), CryoSat-2, Jason-1, Saral-Altika), Satellite-Satellite tracking (CHAMP and GRACE), Satellite Gravity Gradiometry (GOCE). Since summarising the results from all the studies goes beyond the scope of this review article, results from selected studies of satellite gravimetry are briefly mentioned.

Applications of Satellite-derived Gravity for Crustal Studies

Applications of satellite gravimetry in India are reported in several studies related to exploration of natural resources, lithospheric structure, hydrological changes and geodynamics studies. Bhattacharyya *et al.* (2009) generated a composite high-resolution free-air gravity anomaly map for the Arabian Sea from Seasat, Geosat GM, ERS-1/2 and Topex/Poseidon altimeters data. Satellite altimetry derived gravity combined with terestrial gravity data provide enhanced imaging of geological features of Indian penesula and adjoining ocean basins (Majumdar *et al.*, 2001; Mishra *et al.*, 2004 and 2012; Mishra and Tiwari, 2008; Mishra and Rajasekhar, 2005; Tiwari *et al.*, 2007 and 2013; Tiwari and Mishra, 2008; Chatterjee *et al.*, 2007; Mishra and Ravikumar, 2012; Ravikumar *et al.*, 2013a; Ravikumar *et al.*, 2013b; Kumar *et al.*, 2013; Kumar *et al.*, 2014; Rajesh and Majumdar, 2014; Singh *et al.*, 2015), Bay of Bengal (Radhakrishna *et al.*, 2000; Rajesh and Majumdar, 2003; Radhakrishna *et al.*, 2010; Nandi and Rao. 2015; Kar *et al.*, 2015; Rao *et al.*, 2015; Rao *et al.*, 2016; Dubey *et al.*, 2017), continental margins of India (Chand *et al.* 2001;

Subrahmanyam and Chand, 2006; Mishra, 2011; Sreejith *et al*., 2013; Murray, Laxmi, Chagos-Laccadive, 85°E and 90°E ridges (Tiwari *et al*., 2003; Bansal *et al*., 2005; Subrahmanyam *et al*., 2008; Rao and Radhakrishna., 2014; Rajesh *et al*., 2015; Nair *et al*., 2015; Majumdar and Chander, 2016), Western Continental Margin of India (RadhaKrishna *et al*., 2002; Arora *et al*., 2006; Mukhopadhyay *et al*., 2008; Rao *et al*., 2010; Arora *et al*., 2012; Majumdar and Bhattacharyya, 2014; Rao *et al*., 2018), Eastern Continental Margin of India (Singh and Diljith, 2009; Bhanja Bastia *et al*., 2010; Radhakrishna *et al*., 2012; Desa *et al*., 2018), Andaman arc (Grevemeyer and Tiwari, 2006; Radhakrishna *et al*., 2008); Himalayan region (Rajesh and Mishra, 2003; Tiwari *et al*., 2006a,2009a, 2010 and 2014b) Antarctica (Majumdar *et al*., 2018). A 3D lithospheric density model of the Andaman-Sumatra subduction zone is constructed from joint modelling of satellite-derived gravity and geoid data (Yadav and Tiwari, 2018). The geophysical mapping of Singhbhum-Orissa Craton and Jharia Coalfield are carried outusing the GOCE, EGM2008 and EIGEN6-C2 and compared with the in-situ gravity (Pal and Majumdar, 2015; Vaish and Pal, 2015; Pal *et al*., 2016).

A revised gravity anomaly map of the 85°E Ridge (Pal *et al*., 2016) and Bay of Bengal (Narayan *et al*., 2017) was generated utilizing the EIGEN6C4 global gravity model. Singh *et al*. (2015) analysed satellite gravity and geoid anomaly and topography data to determine the 3D lithospheric density structure of the Singhbhum Protocontinent. Kalra *et al*. (2014) interpreted the occurrence of sub-basalt sediments at the margin using the satellite gravity and encapsulated to provide a basis for assessing deepwater petroleum prospect of the entire western margin offshore. Rao and Radhakrishna (2016) carried out evolutiontests based on the statistical estimates, spectral analysis and image enhancement filters have been performed to assess the spatial resolution and quality of Earth Gravitational models (EGM2008, GOCE, DTU13 and SSV23.1) and crustal magnetic field model (EMAG2) over the Indian shield and its surrounding offshore regions.

Hydrogeodesy

Hydrogeodesy is referred to the application of geodetic techniques to the study and monitoring of the terrestrial waters. Dedicated gravity mission senses the spatiotemporal variations of the gravity field caused mainly by the hydrological mass changes in the Indian region and glaciological mass changes over the Himalayan region. Tiwari *et al*. (2009b) estimated a massive loss of groundwater in Northern Indian region at a rate of 54 ± 9 Km^3/yr from 2002 to 2008 utilizing the GRACE data with a combination of hydrological (Fig. 3). The hydrological signal derived from GRACE was also validated with in-situ measurements in India and demostrated the application in the monitoring of water storage (Tiwari *et al*., 2011 and 2014a; Bhanja *et al*., 2016, 2017a; Asoka *et al*., 2017). The GRACE dataset reveals a declining trend of groundwater in different parts of the Indian subcontinent (Tiwari *et al*., 2009b; Khan *et al*., 2013; Dasgupta *et al*., 2014; Banerjee and Kumar 2014; Chinnasamy *et al*., 2015; Verma *et al*., 2016; Gautam *et al*., 2017a; Banerjee and Kumar 2016; Singh *et al*., 2017; Mukherjee and Ramachandran, 2018). Lowering of groundwater storage are caused due to anthropogenic groundwater withdrawals to sustain rice and wheat cultivation in the Ganga basin (Panda and Wahr, 2016; Barik *et al*., 2017). The GWS depletions that constitute about 90% of the observed TWS loss are influenced by a marked rise in temperatures since 2008. Bhanja *et al*. (2017b) noted that the paradigm shift in Indian groundwater withdrawal and management policies for sustainable water utilization appear to have resulted in replenishing the aquifers in western and southern parts of India. GRACE data are also used for detecting significant extreme events, such as flash floods of Mumbai 2005 and Bihar 2008 (Dutt Vishwakarma *et al*., 2013); drought 2015 (Mishra *et al*., 2016; Sinha *et al*., 2017), heat waves (Panda *et al*., 2017). Soni and Syed (2015) estimated the influence of ENSO on ground water storage in major river basins of India.

Hydrological Loading

Indian subcontinent receives a considerable amount of mass in the form of rainfall during south-west (summer) monsoon season and partly during north-east (winter) monsoon period. The mass influence causes the hydrological loading on the crust surface depending on the geological provinces and its intensity. GPS and GRACE data sets can sense this hydrological loading behaviour that may lead to crustal deformation and tectonic movement. Tiwari *et al*. (2014a) analysed the influence of hydrologic loading on vertical

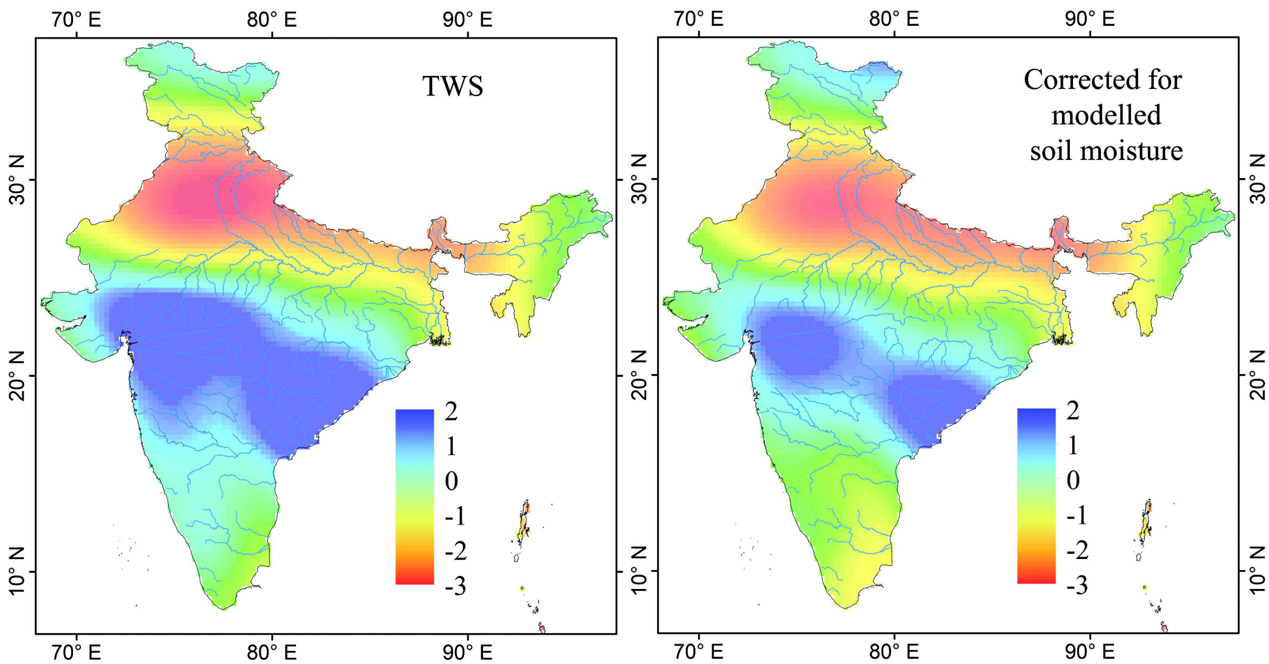

Fig. 3: Rate of change of Total Water Storage (TWS) in the Indian subcontinent (after Tiwari *et al*., 2009b)

deformation over South India (1-2 cm) and compared with data derived from GRACE (Fig. 4). Khandelwal *et al*. (2014) correlated the GPS data with the water load storage in the Ganga plains, with the minimum in displacement coinciding with the maximum storage of water in Ganga plains immediately after the monsoon and vice versa. Such variations also appear to cause the annual variation in the low-magnitude earthquake frequency in the Himalayan region, being relatively more in the winter period. The anthropogenic groundwater unloading in the Indo-Gangetic plains influenced 2015 Mw 7.8 Gorkha, Nepal earthquake that occurred on the MHT beneath the Himalayan arc (Kundu *et al*., 2015). Seasonal variations in the Himalayan region are the most prominent in the vertical and north components of GPS time-series. Gahalaut *et al*. (2017) explained the combined effect of the local reservoir water load and the regional hydrological and atmospheric loading of Tehri reservoir in the Garhwal region of NW Himalaya from the GPS and Interferometric Synthetic Aperture Radar (InSAR) analysis. Kundu *et al*. (2017) demonstrated thatthe evaporation induced unloading in the Himalayan foothills and adjacent Indo-Gangetic plains during the post-monsoon period adds a significant component of horizontal compression to the interseismic contraction at the MHT, which is the primary driving mechanism for the seasonal modulation. The influence of seasonal loads is maximum in the vertical component which decreases in the north and then in the east component in the Garhwal-Kumaun Himalaya (Gautam *et al*., 2017b). Prasad *et al*. (2017) estimated the hydrological loads of Koyna warna region (KWR) from GPS and GRACE of regional water storage and reservoirs storage, which can lead to the perturbation of stress condition as well as pore pressure condition at the depth.

Airborne Gravity Gradiometry

Airborne gravity gradiometry (AGG) can provide a gravity map efficiently over a large, highly inaccessible undulating region in a short period with an accuracy of ~5-10 Eötvos over a wavelength of 400 meters. AGG data can be used for the mapping of subsurface structure with a good spatial resultion. Successfully, the first Airborne Gravity Gradiometer (AGG) survey in India has been carried out through Fugro Falcon Airborne System over the rugged terrain of the Western Ghats in the KWR of Maharashtra to infer subsurface structure as a prelude to the first deep scientific drilling in the region. Joint inversion of AGG

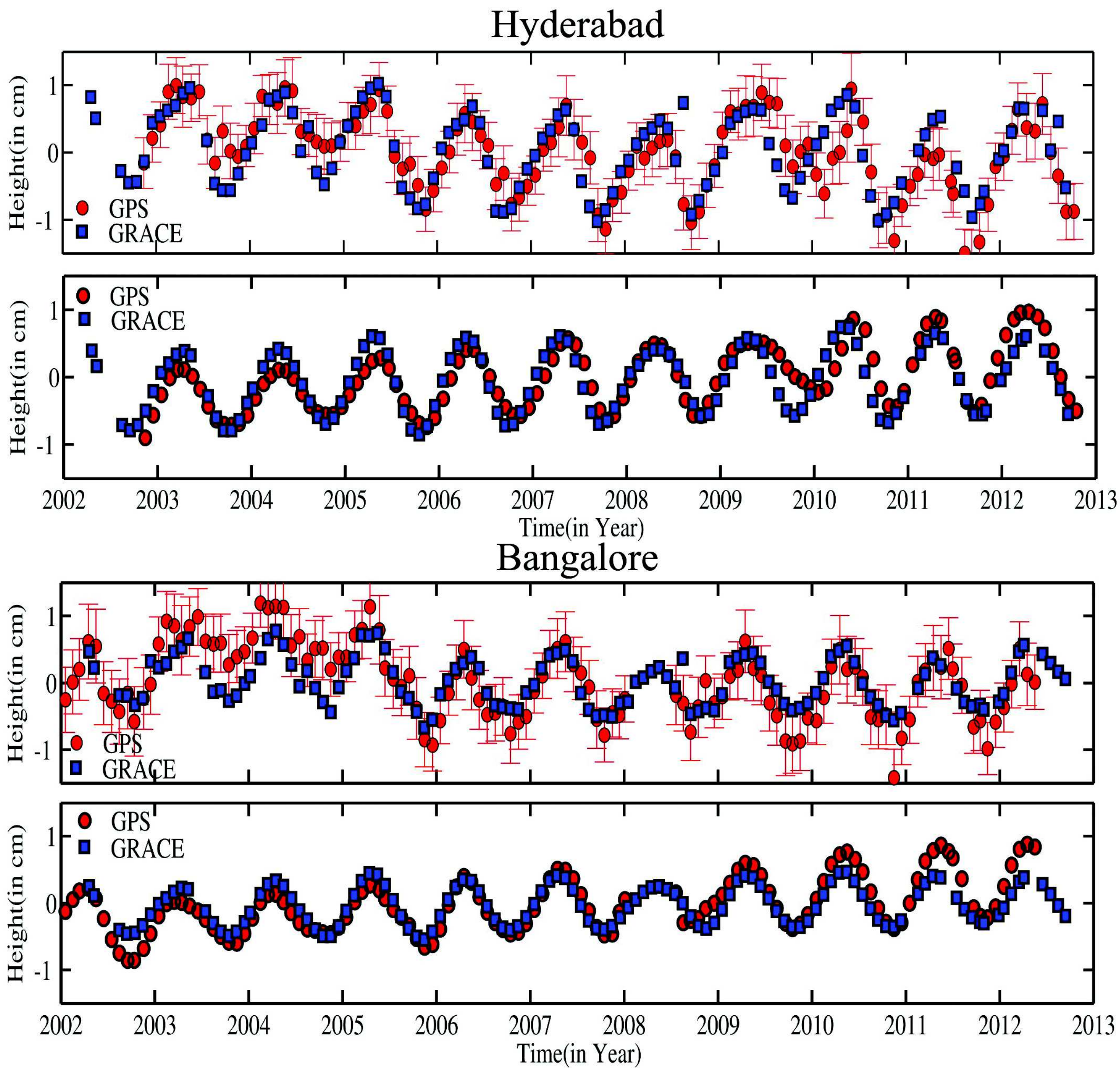

Fig. 4: Comparison of daily and seasonal variations of vertical velocity from GPS & vertical elastic deformation using GRACE data in major cities in Hyderabad and Bengaluru (after Tiwari *et al*., 2014a)

datasets allowed to propose 3D structural setting beneath KWR and across the Western Ghats. In this Survey, AGGM data covering 5,012 line km were recorded along N-S flight paths at an average 120-m drape surface, cutting across the Koyna seismic zone. The subsurface model provides thickness of the Deccan basalts varying from 400 to 1,700 meters in the KWR (Gupta *et al*., 2015). Deccan basalts are thicker on the eastern side of the topographic escarpment compared to the western side (Gupta *et al*., 2017).

Studies for Exploration of Natural Resources

Several central and state government organizations, such as GSI, ONGC, OIL and other exploration companies have extensively acquired gravity data in different basins for regional prospecting. Some of the target areas are basins located in northwest India, Godavari basin, Rewa basin and frontier basins of northeast India. There have also been efforts to map the mineral resources (Mishra, 2011), exploration of hydrocarbons (Singh *et al*., 2012) and sub-basalt sediments (Goyal and Tiwari, 2014). Gravity measurements are made for mineral exploration in different parts of the country by GSI and exploration companies. Several studies at specific localities are taken up for mineral prospecting purposes (http://www.portal.gsi.gov.in). One of the new initiatives was gravity survey for manganese exploration in the Nagpur and Bhandara districts of Maharashtra. Gravity survey carried out in Meghalaya revealed gravity high in the southern part over tertiary rocks corresponding to the high-density intrusive metavolcanics and also due to Khasi Greenstones including epidiorite. Gravity observations recorded for structural mapping and location of mineralized zones in the parts of Singhbhum brought out the disposition of the Copper belt.

Tectonic Geodesy

Tectonic geodesy refers to the application of modern geodetic measurements (InSAR, GPS) of crustal deformation due to numerous earth processes, like plate movement, earthquakes, volcanoes, isostatic adjustments and so on and modelling of measured deformation from GPS to understand processes responsible for them. Researchers from several national research institutes (e.g. CSIR-NGRI,CSIR-4PI, IIG, WIHG, SOI and ISR) and universities have established GPS stations for monitoring the crustal deformation over the Indian shield region and in the plate boundary regions like Himalaya and Andaman. Many campaign mode and about 100 semi-permanent/permanent GNSS/GPS measurements have been providing the up-to-date comprehension of crustal deformation continuously enriching our knowledge of dynamics of the different tectonic regions of the Indian plate (Gahalaut *et al*., 2008; Catherine *et al*., 2015; Mahesh *et al*., 2012a; Gahalaut *et al*., 2013; Jade *et al*, 2017). Analyses of GPS data from peninsular India indicate that there are no significant internal intraplate deformations; however, there are a few regions like a part of Godavari Rift basin which shows crustal deformation (Mahesh *et al*., 2012b). Continuous GPS data from Andaman region have allowed constraining the recurrence time of large earthquakes (Gahalaut *et al*., 2006; Jade *et al*., 2005; Catherine *et al*., 2014). Several new findings reported from GPS observations from NE Himalaya and Karakoram have important implications for the seismic hazard of the region (Jade *et al*., 2007; Mukul *et al*., 2010; Gahalaut and Kundu, 2012). 25 years of GPS data (campaign mode and continuous) from central and western Himalaya offer a new finding of total arc normal shortening, slip and an estimate of locked fault widthof ~ 110 km (Kundu *et al*., 2014).

Tidal Observations

The responsibility of carrying out systematic tidal observations and monitoring of tidal stationswas entrusted to SOI in 1877 and since then data is beingcollected continuously at tidal observatories located along East and West Coasts and also Andaman & Nicobar and Lakshadweep Islands. Sea-Level data from about 24 Tidal observatories, collected during the last 10 decades, is utilized mainly to determine Mean Sea-Level to serve as the Vertical Control Datum for heights for the country, tidal predictions for navigational purposes and for estimation of long time sea level changes. Tide tables are printed a year in advance and made available to National/International users to facilitate their navigational activities. Tiwari *et al*., (2004) analysed the Indian ocean sea level changes and ascribed the changes in terms of warming and cooling of the ocean. The mean sea level (1993-1999) estimated from T/P altimetry (Tiwari *et al*., 2005), which compares well with tide gauge records, seems to be a part of decadal variations of sea level in the Indian ocean.Catherine *et al*. (2014) analyzed the sea level variations from satellite altimetry data and tide gauge from Andaman Islands for tectonic studies. During the past decade, state-of-the-art digital tide-gauges at ~ 30 locations along the Indian coast have been established and connected to the dedicated VSAT network for real-time tidal data transmission to the centrally located hub at National Tidal Data Centre, G&RB, SOI. This near real-time tidal data is also shared with the National Early Tsunami Warning Centre, INCOIS, Hyderabad for the issuance of a tsunami warning in the event of any eventuality. Extensive analysis of tidal data is carried out for extreme events like Tsunami, storm surge, cyclone, etc.

Planetary Gravity Studies

Satellite-Satellite tracking technique can provide recovery of gravitational ûeld with high-resolution data of the Moon with the help of Gravity Recovery and Interior Laboratory (GRAIL) mission. Detailed analyses were carried out by Satyakumar *et al*. (2018)

and GRGM900C gravity anomaliesare derived from GRAIL mission and topography over the Lunar far side covering the major impact basins to understand subsurface structure. The observed nature of gravity anomalies and crustal thickness are attributed to the buried impact crater under this region. The structure and evolution of the near and far side of the Moon have been studied using integrated analysis of Free-air, Bouguer gravity anomalies of the Moon along with morphological and structural information derived from various remote sensing datasets. Gravity anomalies of Venus are also computed using gravity model (MGNP180U) derived from Magellan mission. Inversion of Bouguer gravity anomalies resulted in computation ofcrustal thickness map of Venus.

New Initiatives

Considering the global development in the field of Geodesy, its importance in strengthening the National Mapping and Geodetic organizations and requirement of human resources in this field, a "National Programme on Geodesy" has been launched by the Department of Science & Technology, Government of India, with the following objectives:

1. To build up the capacity in different aspects of Geodesy in Indian institutions.
2. To strengthen the Human Resource Development in Geodesy in the country.
3. To address the need of National Mapping and Geodetic organizations.

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