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Preface

On the behalf of Indian National Science Academy, adhering body to the International Union of Geodesy and Geophysics (IUGG), it is a matter of great pleasure for me to present the report of the activities of Indian institutions and researchers in the field of Geodesy and Geophysics for the period of January, 2011 to December, 2014 to be submitted to the IUGG at its XXVI General Assembly being held at Prague during 22nd June to 2nd July, 2015. This report is presented in a set pattern previously submitted by Indian National Committee i.e. reports on the activities in the individual areas of eight IUGG associations along with a comprehensive list of published works and reports.

Scientific activities related to IUGG in India over the past four years have been very exciting. Several new programmers are initiated. GNSS/GPS networks were established to carry out continuous and campaign mode observations at more than 100 sites covering active tectonic regions like Andaman and Himalaya and peninsular India, some of them co-located at tide gauge installations. For the first time, airborne gravity-gradiometry measurements in India were carried out over the Koyna region. A mega project of deep scientific drilling (6-8 km) in the Koyna region is initiated to better understand the mechanism of reservoir-triggered earthquakes. Several other progaremmes like aquifer mapping, oceanographic, atmospheric and cryospheric studies are were undertaken during this period.

Rajan and Thamban reported on Cryospheric research and emphasized on the new initiatives in India. The scientific details related to gravimetry and geodesy is compiled by Tiwari, emphasizing new gravimetric and geodetic initiatives. Arora and Veenadhari have reported on Geomagnetism and Aeronomy and focused on India's data contributions and models from critical geographical locations. P. Rajendra Prasad presented a detailed report on hydrological studies in India and India's water scenario. Dimri and Mohanthy have brought together a range of atmospheric and meteorological research contributions made by Indian scientists. Shenoi and colleagues reported on new trends in oceanographic research and India's role in the tsunami, cyclone and ocean surges warning in the Indian Ocean regions. Gahalaut and Kayal have presented the report on Seismology and Physics of Earth's Interior. Pandey and Krishna reported on Volcanology and Earth's Interior, and highlighted important findings in the peninsular India.

I wish to thank all those individuals who have contributed articles for this Report and organizations which provided information for compiling the Indian contributions in the specific research areas of IUGG associations. I would also like to thank the IUGG National Committee members and officers of the Indian National Science Academy, for their help in bringing out this Report. I sincerely acknowledge Dr. M.R.K.P Rao for his efforts for critically going through the reports. I hope that the present report offers a useful overview of the geodetic and geophysical activities in India during the past four years, in particular for the younger colleagues whom it provides backdrop information for future research.

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Gravimetry and Geodesy in India during 2011-2014

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Introduction:

Conventionally, geodesy and gravimetry deal with the determination of the shape of the Earth and the distribution of the masses within the Earth and have extensively been utilized as tools in resolving a wide variety of geophysical problems related to the dynamic Earth system. Since the last few decades or so, these studies have been playing a vital role in many societal applications including mapping and exploration of natural resources. Geodesy is a scientific interface in facilitating the combination of satellite observations with those gathered on ground making all Earth observations interoperable. With the advances in technology, particularly satellite based observations have lead to a considerable progress in the geodetic and gravity research and their applications for societal benefits. Geodetic measurements are used in India for seismotectonic and crustal movement studies, tunnel alignment besides ascertaining structural stability of various engineering structures viz., hydroelectric projects, structural stability of historical monuments such as Taj Mahal and Qutub Minar etc.. This report presents the compilation of activities of Indian scientists and institutions in the scientific research related to gravimetry and geodesy.

Geodetic observations for reference stations

Geodetic & Research Branch, Survey of India (G&RB SOI) has set up a Ground Control Point (GCP) Library, as a part of which 294 primary cotrol points at the spacing of 250-300 km apart and 2252 GCP Library pillars have been established at an interval of about 25-30 km to cater the needs of horizontal reference points. Observations and computations have been completed along with network adjustment of 45,000 ln km of precise spirit levelling run as a part of redefining Indian vertical datum.

Precise Gravity Observations

The absolute gravity (AG) observations across India are being carried out primarily by CSIR-NGRI using Micro-g LaCoste FG5 absolute gravimeter. The AG observations comprised of regular repeat measurements over a network of existing absolute gravity sites throughout India to provide a time series for mass changes and vertical deformation and repeat observations at the site of Superconducting Gravimeter (SG) located in the Himalayan region for drift corrections and calibration of SG records. AG observation stations are also used as reference gravity stations and utilized for metrological applications as well. Gravity variations using gPhone gravimeter are being

continuously recorded at Warna, Maharashtra, a seismically active region of the peninsular India for investigation of gravity changes related to seismic activities. The Superconducting Gravimeters are in operation at two locations in India, Bhuj, western India by ISR, Ahmadabad and at Ghuttu, in the north by WIHG, Dehradun. The SGs continue to provide a high precision record of the time variation of gravity at these locations. SG observations at both locations are collocated by other geophysical observations with the primary objective of earthquake precursory studies.

Local Geoid Determination

Global Positioning System (GPS) is now often used for scientific and societal applications however the orthometric heights from GPS measurements require precise information of geoid undulations. A few projects are undertaken to determine the geoid undulation in the selected regions. Geoid undulations over a part of southern Indian region are computed from terrestrial gravity data using remove–restore technique that involves spherical Fast Fourier Transform (FFT) to compute 'Stokes' coefficients and compared with geoids from global geopotential model and GPS-levelling data. An agreement between GPS-levelling data and global geopotential model is was found on regional scale. However, geoid from GPS-levelling over a small region is considerably different (in meter) suggesting determination of gravimetric geoid for local applications. Geoid undulations are also derived from Lidar survey and GTS benchmarks over the Kosi and Mahandi basins and compared with the GOCE derived geoid heights. A bias of 1.5 m with reference to the ground geoid is reported.

Airborne Gravity Gradiometry

The development of airborne gradiometry with an accuracy of ~5-10 eötvos over a wavelength of 400 m and the recently launched gravity gradiometer satellite mission GOCE have offered a fresh impetus to gravimetry and its application in the subsurface exploration. Airborne gravity gradiometery can provide a potential map easily over a large, highly inaccessible undulating region in a short period of time. Taking the advantage of these developments, 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 Koyna-Warna region of Maharashtra to infer subsurface structure as prelude to the first deep scientific drilling in the region. Joint inversion of AGG datasets allowed proposing 3D structural setting beneath Koyna-Warna region and across the Western Ghats.

Gravity studies for Tectonics and Geodynamics

Most the Indian researchers engaged in the observation and modelling of the earth's gravity field are focussing in 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 the peninsular India. As summarizing the results from all the studies is beyond the scope of this report, results from selected studies are briefly mentioned. Nevertheless, publication list includes most of the work published on the tectonic and geodynamic studies.

Joint modelling of free air gravity, geoid anomalies and topography data provided a 3D crustal and lithospheric density structure of southern Indian shield, Sri Lanka and adjoining oceans. A combatively thin and hot lithosphere beneath the southern block of Southern Granulite Terrane including Sri Lanka is proposed for isostatic compensation to explain the high topography, gravity, geoid and crustal temperatures. 3D modelling of gravity field across western continental margin of India suggested the variation of crustal and lithospheric thicknesses and allowed to propose spatio-temporal evolution of the western margin of India. Modelling of long wavelength gravity field across India has put forward a suggestion of difference in the upper mantle structure/density of the areas north and south of Narmada-Tapti region. A lithospheric model across Andaman subduction zone is proposed based on analyses and modelling of gravity data. Also, deep density distribution under the adjoining oceanic regions of Bay of Bengal and Arabian Sea are deciphered based on analyses and modelling of gravity data with constraints from other results.

Gravity data in the eastern and the western part of Himalaya are recorded along roads at every one km. Combining the existing data with global gravity model, density structure across Himalayan collision zone and syntaxes belts are inferred and the structures are interpreted in terms of present tectonics. Satellite altimetry data are utilized for generation of high resolution geoid and gravity data of the Indian Ocean. These data are used for understanding the structure and evolution of the Indian Ocean lithosphere, detailed understanding of the isostasy and crustal architecture of aseismic ridges and continental margins.

Studies for Exploration of Natural Resources

Central and state government organizations, such as Geological Survey of India (GSI), Oil and Natural Gas Corporation (ONGC), Oil India (OIL) and other exploration companies have extensively acquired gravity data in the different basins for regional prospecting. Some of the target areas are basins located in the northwest India, Godavari basin, Rewa basin and frontier basins of north east India. There have also been efforts to map sub-basalt sediments in the central India by CSIR-NGRI, Hyderabad. Similarly, gravity measurements are made for mineral exploration in the different parts of the country by GSI and other exploration companies. One of the new initiatives was gravity survey for manganese exploration in the Nagpur and Bhandara district 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. The gravity low in the northwestern part of surveyed area of Meghalaya indicates deepening of basement. Gravity observations recorded for structural mapping and locating mineralized zones in the parts of Singhbhum brought out the disposition of the Copper belt. Several other studies at specific localities are taken up for mineral prospecting purposes (http://www.portal.gsi.gov.in).

Theoretical Developments

Theoretical development to analyse and model gravity data has been the continuous efforts of researchers in the universities and research organizations. During the reporting period, a method coupled with a GUI based computer program in JAVA, has been written to interactively model the gravity anomalies in addition to the algorithm of gravity inversion in the space domain is developed and applied to estimate parameters of strike-limited listric fault. A new technique by combining singular value decomposition and multifractal is proposed to separate the gravitational anomalies from its background for delineation of subsurface features. A successful demonstration using synthetic and field data has been made for mapping sub-basalt sediments using wavelet analyses of gravity and magnetic data simultaneously.

Tidal Observations

During the past couple of years, state-of-the-art digital tide-gauges at ~ 30 locations along the Indian coast have been established. These tide gauges are 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 issuance of tsunami warning in event of any eventuality. Extensive analysis of tidal data are carried out for extreme events like Tsunami, storm surge, cyclone etc. which are needed for delineation of highest tide level with 100 year return period.

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 modeling of measured deformation from GPS to understand processes responsible for them. Indian researchers and officials from several national research institutes (e.g. CSIR-NGRI,4PI, IIG, WIHG, SOI, ISR) and universities have established GPS stations for monitoring 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 up-to-date comprehension of crustal deformation

continuously enriching our knowledge of dynamics of the different tectonic regions of Indian plate. Analyses of GPS data from the peninsular India indicate that there are not significant internal intraplate deformations; however there are a few regions like a part of Godavari Rift basin which do show crustal deformation. Continuous GPS data from Andaman region have allowed constraining the recurrence time of large earthquakes. Several new findings reported from new GPS observations from NE Himalaya and Karakoram have important implications on seismic hazard of the region. 13 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 width (~ 110 km).

GNSS measurement of the atmosphere

Since the electromagnetic signals from the satellites propagate through our atmosphere before reaching Earth, these signals provide information about the state of the atmosphere. Variations in the Total Electron Count (TEC) measured from GPS are exploited to infer processes related to atmosphere and as well events happening in the earth. Changes in the TEC are observed during solar cycle. Also, TEC changes are found to be anomalous before the main earthquake events. The TEC anomaly appeared as local TEC enhancement in the vicinity of the earthquake epicentre prior to its occurrence.

GPS Data Centre

Earth System Sciences Organization (ESSO), Ministry of Earth Sciences (MoES) has supported several projects, in which a GNSS network of about 100 permanent and semi-permanent GPS/GNSS receiving stations are established. Data from these stations and other GPS stations set up are being archived at Indian ESSO-National Centre for Ocean Information Services (INCOIS), Hyderabad. These data are available to researchers on request following the data sharing policy (http://www.isgn.gov.in).

Estimating Mass Variability from GRACE Data

Time variable gravity data from GRACE satellite mission have been utilized for evaluation hydrological mass changes in the Indian region and glaciological mass changes over Himalayan region by different institutions. A number of analyses substantiated the earlier finding of large water mass loss from northern Indian region proposed from GRACE data. A couple of studies compared ice mass variability from GRACE and other remote sensing and in-situ observations.

Gravity Studies of Moon and Venus

Recently Space Applications Centre (SAC), ISRO has initiated the gravity studies of Moon and Venus. Gravity anomalies are computed using recently released high resolution gravity model:

GL0900C of "Gravity Recovery And Interior Laboratory (GRAIL)" mission. The structure and evolution of selected mare basins of 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. Crustal thickness map of Venus was computed by inversion of Bouguer gravity anomalies. Preliminary interpretation of gravity anomalies, derived crustal thickness map vis-a-vis regional tectonic features has been carried out.

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