National geospatial policy: status of the Indian geodetic data

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The National Geospatial Policy has well communicated the need for sharing geospatial data, with an emphasis that these data must refer to the geodetic/topographic database of the Survey of India (SoI). SoI has been collecting, processing, archiving and disseminating geodetic data for over a century. Several stakeholders are using these datasets, viz. Government, academia, industry and researchers, for their respective applications. SoI also updated its database as and when required due to the introduction of sophisticated and precise instruments, accuracy requirements, or to improve the database scientifically. Although the results or policies involving the geodetic data are provided in the literature, there is limited discussion of the data themselves. This article provides comprehensive information about the geodetic data available to Indian users for various applications. The data discussed here are the horizontal and vertical positioning, gravity, geoid model and digital elevation models.

Keywords: Geospatial guidelines and policies, geoid model, horizontal and vertical positioning, topographic database.

THE National Geospatial Policy guidelines broadly mention that all the topographic databases must be referred to the Survey of India (SoI) database, thereby maintaining consistency in the geospatial data and avoiding duplication in data collection by several stakeholders[1–3]. As such, it is mentioned that SoI shall prepare and update the national topographic database and provide the national geospatial frame. Further, SoI will take necessary measures to simplify procedures so that its data can be easily assessed by citizens, industry, academia, researchers, Non-Governmental Organizations (NGOs) and the Government.

The first two national foundation data asset themes are (i) geodetic reference system (a system for uniquely referencing spatial information in space as a set of coordinates (x, y, z) and/or latitude and longitude and height, based on a geodetic horizontal and vertical datum), and (ii) elevation and depth (digital elevation models (DEMs) for land, ice and ocean surface, including terrestrial elevation, bathymetry and shoreline). Further, threshold values for geospatial guidelines have been provided. (i) On-site spatial accuracy shall be 1 m for horizontal or planimetry and 3 m for vertical or elevation. (ii) Gravity anomaly shall be 1 mGal. There is also a threshold value provided for bathymetric data, but it is not discussed in this article.

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From the above recapitulation of a few important aspects of the geospatial guidelines and policy, it becomes inevitable that the various stakeholders use SoI data to maintain geospatial data consistency in India. Therefore, the primary requirement is to understand the dataset provided by SoI, which is to be used as a reference dataset for observing further geospatial data and developing geospatial data products. This article provides a detailed discussion of the dataset concerning the first two national foundation data asset themes. These are horizontal positioning, vertical positioning, gravity, geoid model and DEM, which we collectively refer to as geodetic data.

India is the seventh largest country in the world with the most varied topography that comprises the Gangetic Plains, desert, Aravalli and Vindhya ranges, plateaus, Eastern and Western Ghats, Himalaya, and a long peninsular coastline (Figure 1). The Government of India (GoI) depends significantly on the use of geospatial technologies in various initiatives and programmes like Gati Shakti, Survey of Villages Abadi and Mapping with Improvised Technology in Village Areas (SVAMITVA), Digital India Land Records Modernization Programme (DILRMP), National Hydrology Project (NHP), National Mission for Clean Ganga (NMCG), etc. According to the Geospatial Artha report, the geospatial economy of India may grow up to Rs 63,100 crore by 2025 (ref. 4).

Almost all the ministries under GoI depend on the geospatial sector for providing improved services to the citizens (e.g. National Centre of Geoinformatics; https://ncog.gov.in/users.html). To aid the Government's programmes, i.e.

to develop geospatial products, services and solutions, the Indian academia, researchers and industry are also actively involved. Further, academia and research organizations are involved in scientific studies on geospatial technologies. The National Geospatial Policy has been helpful in attracting industry, academia, researchers, and the Government to use geospatial technologies in their respective applications.

However, the whole of the geospatial sector has its basis in geodetic data, which is further based on reference surfaces, commonly known as datums. Similarly, some geodetic products are crucial inputs in various applications, such as the geoid model or DEM. Any user can obtain the horizontal position using a global navigation satellite system (GNSS), gravity using a gravimeter, heights using levelling or GNSS, (global) geoid models from the International Centre for Global Earth Models (ICGEM) and DEM from different freely available sources. However, to maintain consistency in the data, which is also the main objective of the new geospatial guidelines and Policy, the data must refer to some national datum.

In India, SoI has been instrumental in collecting and providing most of the geodetic data and products to all the stakeholders. The organization has defined Indian geodetic datums with the available data and methods, but given the present-day accuracy and application requirements, the geodetic datums need to be redefined. For example, if the DILRMP or SVAMITVA programme is executed without a static horizontal datum, observations may have to be repeated after a few years (15–20 years). This is because the coordinates obtained in the WGS84 datum (and not in a national datum) will change with time, primarily due to the dynamicity of the tectonic plates. Therefore, such projects must be referred to a static horizontal datum instead of a dynamic datum (e.g. WGS84). The proposed strategy for the redefinition of the geodetic datums is not covered in this article but will be discussed in another article dedicated to the way forward for establishing the Indian Geodetic Reference Frame (InGReF), i.e. redefining the Indian geodetic datums.

It should be noted here that we have two geodetic networks in India, one for horizontal positioning and another for vertical positioning, i.e. there are limited benchmarks/ Ground Control Points (GCPs) where both the horizontal coordinates and the levelling heights are available. Recently, SoI has taken up a massive task to connect GCPs with levelling networks and take GNSS observations on the levelling benchmarks. This combined information – latitude, longitude, ellipsoidal height and levelling height – forms an important dataset for various tasks, including validation of geoid and DEMs, and calculating hybrid geoid.

The following sections are dedicated to the five geodetic data/products available for Indian users: horizontal position, vertical position, gravity, geoid and DEM. First, these are explained briefly, followed by details in the Indian context. The collection, processing and archival of these datasets involved tremendous and appreciable efforts by SoI. However, the discussions may elicit a few questions that users would like to discuss before procuring/using the SoI geodetic data for referring to their respective geodetic projects in view of the new Geospatial Policy.

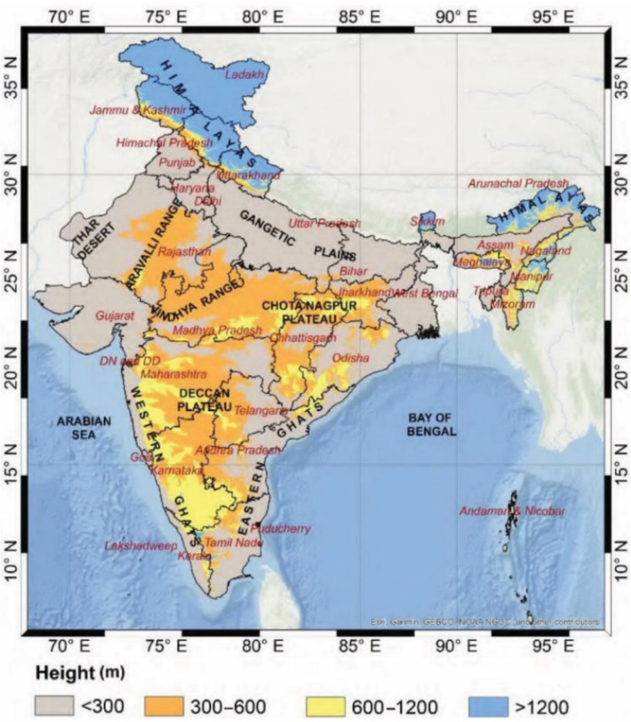

Figure 1. Indian topographical landforms.

Horizontal positioning

The horizontal position refers to the two-dimensional positional information required to locate any point on the Earth, disregarding its topographical information. The 2D coordinates refer to a mathematical surface of the Earth known as the reference ellipsoid. It can be either a locally best-fitting ellipsoid, e.g. Everest, or a globally best-fitting ellipsoid, e.g. WGS84. Although there can be a different representation of these coordinates depending on the choice of the coordinate system, most commonly these are provided in the cartesian coordinate system (X, Y) or curvilinear geodetic coordinate system (geodetic latitude and longitude), which are now easily obtained using GNSS. Most location-based services require only 2D positional information. GNSS also provides height information (known as ellipsoidal height), which is geometric in nature.

Until a few decades ago, the horizontal position in India was referenced to the Great Trigonometric Survey (GTS) stations with the Everest ellipsoid. There have been three adjustments known with the GTS stations, i.e. the adjustment of 1880, 1916 (important for Burma), and the readjustment of 1937. Details of all these three adjustments are provided in Bomford[5]. One can also refer to de Graff Hunter[6] for the

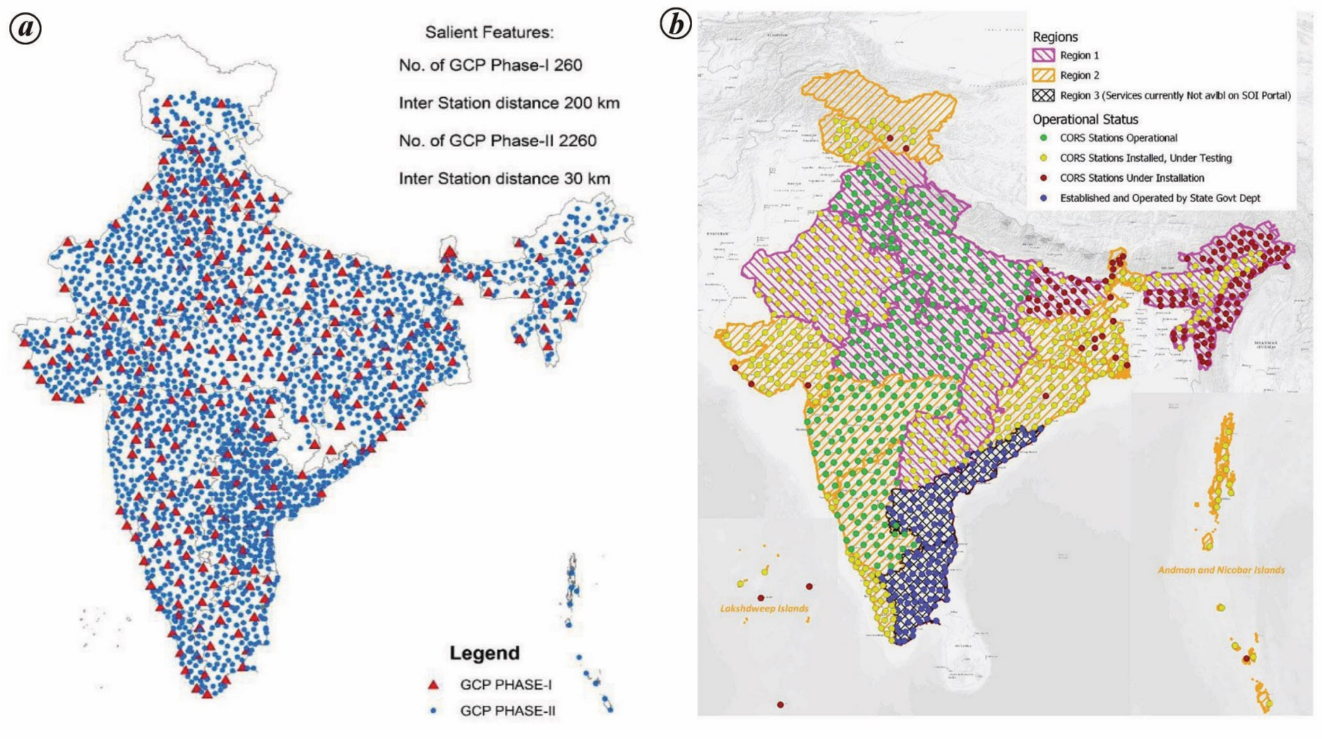

Figure 2. *a*, GCP Library (source: ref. 47). *b*, CORS network (source: ref. 48).

effect on station positions due to the choice of local and international spheroid and foot-to-metre conversion for India. The different numerical values of the semi-major axis associated with the Everest ellipsoid have been discussed by Featherstone and Goyal[7].

All the topographic maps were initially published in the Everest datum. Noting the significance of using the international spheroid, SoI decided, around 2005, to publish a new set of maps from the existing Everest datum to the WGS84 datum. Some transformation parameters are available in the technical report of the National Imagery and Mapping Agency (NIMA)[8], which are also being used in different open-source or proprietary software. However, these are based on only seven common stations, so the uncertainties are high. The original transformation from Everest to WGS84 was carried out zone-wise, i.e. there are different transformation parameters for different regions of India. No official transformation parameters or procedures are available to the public. However, SoI provides the transformed coordinates according to user requirements.

As a step towards working with the global ellipsoid, SoI planned the ‘Creation of National Ground Control Points (GCP) Library for India’ to be carried out in three phases[9]. The total number of established GCPs in the first and second phases are reported to be 292 and 2252 respectively[9] (Figure 2 *a*). Similar information but with a different number of GCPs is also provided in reports by the National Disaster Management Authority (NDMA)[10] and the Department of Science and Technology (DST), GoI[11]. Understandably, the different number of GCPs may be a typographical error, or a number of points may have been added or destroyed with time. However, the number of GCPs becomes important because it is mentioned that the first phase network is adjusted, the solution of which will depend on the number of GCPs. It must be noted here that this adjusted first-phase GCP network is also sometimes referred to as the Indian geodetic reference frame, Indian geodetic datum or National Spatial Reference Frame. However, we could not find any information on the processing and adjustment of this network to define the national datum.

Limited documents with comprehensive information about the GCP Library are available in the public domain. These have mentioned different ITRF solutions (ITRF2005 or ITRF2008) for the GCP Library[10,12]. There is also confusion regarding the choice of a global ellipsoid, i.e. WGS84 or GRS80. The choice of an ellipsoid is important for consistency because we observe that in India, WGS84 is utilized for horizontal positioning while calculating gravity anomalies involves GRS80 (refs 13, 14; pers. commun., 2021). Further, ‘epoch’ is also reported inconsistently. The epoch for which an ITRF solution is given, e.g. ITRF 2008 epoch 2005.0, signifies that the ITRF2008 is realized such that there are null translation parameters, translation rates, scale factor, scale rate, rotation parameters and rotation rates (with respect to the previous ITRF solution, ITRF2005 in case of ITRF2008) at epoch 2005.0. Another way in which the epoch is used is to refer to the coordinates of the desired stations (e.g. National GCP Library) for any given date (decimal years) using the plate velocity models. It is important to make a distinction because there is confusion about the horizontal positional data of GCPs to be in ITRF2005 epoch 2008.0 or ITRF2008 epoch 2005.0 (refs 10, 12, 14; pers. commun., 2022). The GCP data can be procured from SoI. However, in the pre-geospatial guidelines era, no information was shared on the error estimates of the data. We hope that more details will be made available while procuring the GCP data to maintain consistency in the heterogeneously collected data (by various stakeholders).

Recently, SoI has also undertaken the enormous and significant task of establishing continuously operating reference stations (CORS) all around India. All the required information on the various services and data available from these CORS networks, along with video tutorials, is available in detail at the SoI CORS website (https://www.cors.surveyofindia.gov.in/). The current setup seems more suitable for real-time kinematic (RTK) positioning applications. Information on the operational CORS, installed CORS under testing, and those under installation is available from the SoI CORS website, which is regularly updated. As of February 2023, the CORS network in Uttar Pradesh, Uttarakhand, Haryana, Punjab, Madhya Pradesh, Maharashtra and Karnataka is functional (Figure 2 *b*). Once the desired CORS network has been set up, the data can be checked for repeatability and reliability. Henceforth, the most precise stations must be identified to be included in the stochastically constrained network adjustment, which can be the basis of the redefined Indian horizontal datum.

Vertical positioning

Vertical positioning, i.e. height, is useful for various applications such as military planning and guidance, infrastructural development, disaster management and mitigation, etc. However, the term 'height' is not self-explanatory because different heights or height-related terms are available in geodesy and surveying depending on the vertical reference surface being used, e.g. geoid, quasigeoid or ellipsoid. The height with reference to an ellipsoid is known as the ellipsoidal height (i.e. the height we obtain using GNSS), which is geometric in nature, i.e. it does not follow the water-flow criterion. Hence, ellipsoidal heights are not used in large-scale infrastructure development. The contours on the topographical maps of SoI are generated using heights from the levelling network, i.e. the physically meaningful heights, also generally known as heights above mean sea level (MSL) or orthometric heights (although the two are not the same). The benchmarks established during the levelling exercise form the basis of the vertical control of almost all the major infrastructural development projects in India.

There are two Indian vertical datums (IVDs) defined by SoI; one in 1909 and the other in 2018 (refs 14, 15). The former IVD is more commonly known as the Indian mean sea level datum (mentioned here as IVD1909), while the latter is known as the redefined Indian vertical datum 2009 (mentioned here as IVD2009). IVD1909 was based on constraining the MSL of nine tidal observatories, to zero. Constraining to zero means that the heights of the nine-tide gauge benchmarks (TGBM) were transferred from the respective tidal observatories considering that the MSL estimate at each of these nine observatories is the same, i.e. zero. It should be noted that although the MSL estimate at the nine tide observatories was considered to be at the same level, i.e. zero, the Bay of Bengal is, on average, ~320 mm higher than the Arabian Sea[16]. This situation was also observed during levelling for IVD909 but was left unexplored for the future. Such an approach of constraining the levelling network to the multiple tidal observatories with the same MSL estimate leads to a north–south tilt in the datum, thus causing systematic biases[17]. The spirit levelling heights were transformed to dynamic heights, which were further transformed to orthometric heights by applying the orthometric correction. Due to the non-availability of sufficient portable gravimeters, normal (theoretical) gravity was used with the levelling. Hence, the heights so obtained were normal orthometric heights[18].

IVD2009 was based on constraining the geopotential at eight tidal observatories to the same value. Constraining to the same value indicates that the local geopotential value was calculated by taking an average of the geopotential values at eight tidal observatories to decide the geopotential value for IVD2009. It implies that although the average geopotential at eight tidal observatories varied from 62,636,856.54 to 62,636,861.80 $m^2 s^{-2}$, the final value for all eight stations was fixed at 62,636,859.40 $m^2 s^{-2}$. The

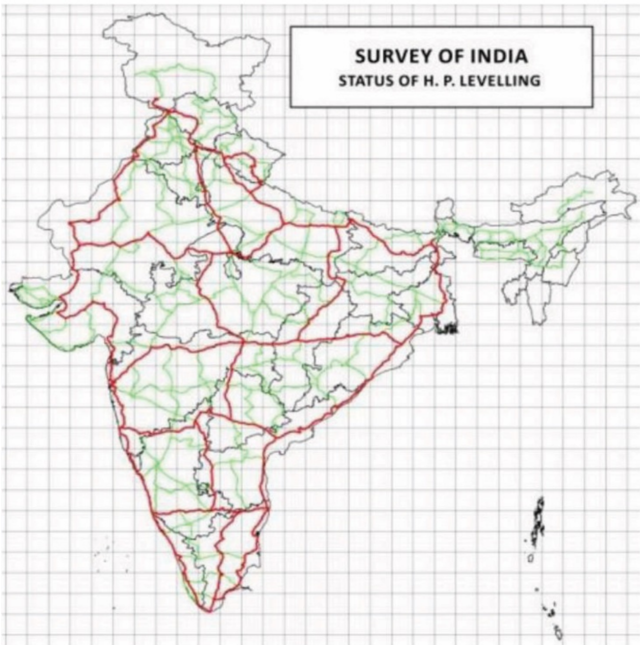

Figure 3. Levelling net for IVD2009 (red line shows primary network). (Source: ref. 19).

difference between the final adopted geopotential value and the maximum and minimum values (from eight stations) translates to a difference of approximately 0.29 and –0.26 m respectively. In IVD2009, gravity readings were also taken along the levelling lines (Figure 3, ref. 19). Hence, the heights that are referenced to IVD2009 are Helmert's orthometric heights. Levelling heights can also be procured from SoI. However, in the pre-geospatial guidelines era, the values were provided with truncation at the centimetre level (e.g. 123.45 m), which may now change after the new Geospatial Policy.

Gravity

Gravity is the resultant of the mass attraction of the Earth (gravitation) and its rotation (centrifugal). Further, the Earth's mass distribution and its rotation vary with time. Thus, gravity information is essential for various geodetic, geophysical, geodynamic and oceanographic applications along with orbit determination[20]. In India, primarily SoI has done appreciable work in geodetic applications with gravity data, while the National Geophysical Research Institute (NGRI) has undertaken various scientific applications, as have other organizations[21]. Concerning this article, for geodetic purposes, precise gravity information can be used to determine horizontal and vertical positions[22]. Although precise horizontal positions are now obtained using GNSS, gravity information will always be necessary to obtain precise orthometric heights[20].

SoI began absolute gravity measurements in 1865 using brass pendulums. Five hundred and sixty-four pendulum measurements were acquired throughout the country in two separate phases, i.e. 1902–25 and 1926–39. After the Second World War, gravity surveys were continued for further densification using Frost and Worden gravimeters. A gravity map of India was developed in 1956 at a scale of 1 : 12,000,000 and a contour interval of 20 mGal (ref. 23). This gravity map was constructed using data from around 3000 stations.

The gravity base station for the Indian National Gravity Datum 1963 (INGD63) is situated in Dehradun, Uttarakhand. The absolute gravity value of this base station in INGD63 is 978,064.0 mGal and 978,049.09 mGal based on the International Gravity Standardization Net 1971 (IGSN71). Hence, a correction of ~14.9 mGal (which originates from an error at Potsdam) is generally applied to the data observed in INGD63 to obtain the corresponding value in IGSN71.

During the late 1950s to the mid-1970s, organizations such as the Geological Survey of India (GSI) collected gravity data. The old and new data were compiled and transformed to a common datum (INGD63) to prepare the gravity map of India with a 10 mGal contour interval[24]. We were unable to obtain any information on how the different data were transformed into the same datum. This map was published in 1975 on a scale of 1 : 5,000,000.

Later, due to the requirement for updated and comparably precise gravity data, it was decided to revise the gravity map of India using the data collected by SoI, GSI, NGRI, Oil and Natural Gas Corporation (ONGC), and Oil India Limited (OIL) under various projects[25]. A total of 143,786 gravity data points were observed by these organizations, which were archived at GSI, Hyderabad. However, only 51,356 data points were selected to maintain uniform coverage over the entire country. These points were reprocessed to refer to IGSN71, but the reprocessing steps are not available in the literature. The final output was a revised gravity map series of India (GMSI) 2006 that comprises five sets of gravity anomaly maps, including a free-air anomaly map and a Bouguer anomaly map, both at a 1 : 2,000,000 scale. These are the latest gravity maps computed/compiled for India.

Recently, SoI has started reobserving gravity data all over the country. An A10 absolute gravimeter has been procured, and a few absolute gravity points have been established. The absolute gravity value is transferred from an established absolute gravity benchmark to that in the region of interest using relative measurement. The absolute gravity at the new benchmark is then used for further densification of absolute gravity points in that region. In the past few years, approximately 31,000 gravity points have been observed by SoI (pers. commun., 2022). However, it should be noted that these observed gravity values do not refer to any national gravity datum.

Geoid model

The geoid is an equipotential surface of the Earth's gravity field that is best approximated by the ocean at rest. All terrestrial geodetic and engineering surveying measurements are made after aligning the vertical axis of the instrument orthogonal to an equipotential surface. The geoid, therefore, is the best candidate for a reference surface, especially for heights. Although geoid has numerous scientific applications, including subsurface mass anomaly structures, plate tectonics, earth rotation, oceanic lithosphere, etc., the geoid is also computed to be adopted as a national vertical datum. Canada and New Zealand have already adopted geoid (and quasigeoid respectively) as the national vertical datum, and the USA is following suit. SoI has also suggested adopting a gravimetric geoid model as the new vertical datum for India. The most useful application of the geoid model is for the surveyors to effortlessly transform the GNSS-obtained ellipsoidal heights to orthometric heights. Furthermore, a precise geoid can be used with GNSS as an alternative to the tedious, laborious and costly levelling exercise.

James de Graaff Hunter compiled the first geoid map for India in 1922 based on astrogeodetic observations referred to an international spheroid[26]. In 1951, SoI also provided a geoid map for India[27]. During the 1970s to mid-1980s, a few other gravimetric and astrogeodetic geoid-related studies were conducted in the country, with respect to both Everest and GRS67 ellipsoids[28–31].

From 2007 onwards, mostly gravimetric geoid-related studies in India are available in the literature[19,32–36]. A detailed review of these geoid models has been presented in Goyal[37]. Although a few Indian gravimetric geoid models are available in the public domain (Figure 4), an official and reliable model is still elusive[38]. The efforts so far either include a less meticulous computational framework or data of unknown qualities, both of which resulted in the non-availability of a precise gravimetric geoid model for India.

SoI is making a laudable attempt at consistent gravity data collection for the whole country, while the academic institutions are developing their software and improving methods of geoid computation[37,39,40]. Thus, a collaborative effort of SoI and academic and research organizations is the need of the hour if we need a precise geoid model for India in the near future. SoI has calculated α and β versions of INDGEOID, but limited information on their computation and access to the public is available with regard to the two versions.

Digital elevation model

DEM is a 3D representation of the bare ground (topographic) surface of the Earth, excluding trees and man-made structures. A digital surface model (DSM) is a representation of the surface sensed, which includes trees and man-made structures. Digital terrain model (DTM) is another terminology that is used synonymously with DEM and DSM. However, in contrast to DEM and DSM, which are raster datasets, DTM is a vector dataset composed of regularly spaced points and natural features such as ridges and break lines. A DTM augments a DEM by including linear features of the bare-Earth terrain. The applications of DEM, DSM and DTM are well documented in the literature[41,42].

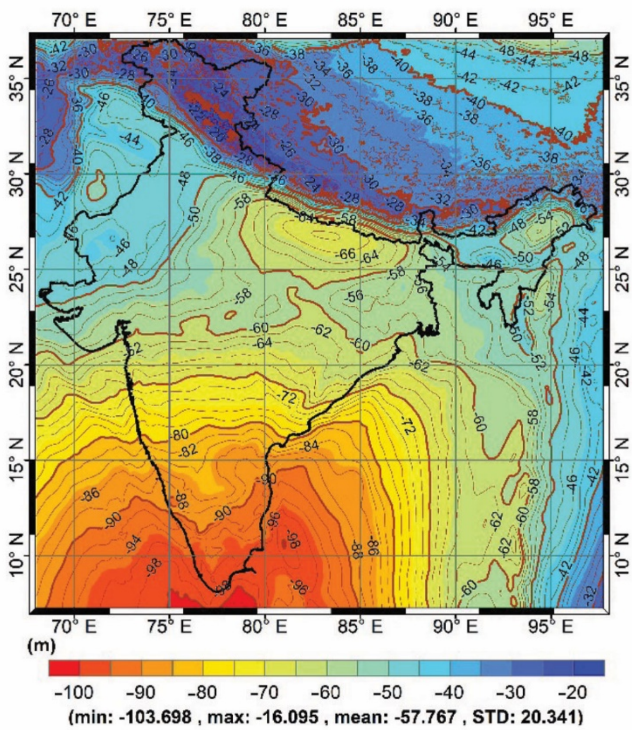

Figure 4. Indian gravimetric geoid model (source: ref. 39).

It should be noted that most of the freely available global digital height models are generated by processing the remotely sensed images and hence, the primary output is a DSM (e.g. SRTM, ASTER), which is sometimes synonymously also used in those applications that strictly require a DEM, e.g. applications requiring water-flow mapping. The Indian CartoDEM is a DSM and not a DEM. However, efforts by SoI to digitize the contours from the topographic maps will result in the required DEM. The accuracy assessment of different freely available DSMs and DEMs in India has been undertaken by many researchers, yet a consistently precise DEM/DSM is still not available for the country[43,44]. A way forward for generating a high-resolution, precise national DEM could be LiDAR mapping and processing (to separate ground and non-ground points) and augmenting it with a precise gravimetric geoid model.

There are two DEMs for India, precisely, one DSM, i.e. CartoDEM and one DEM developed by SoI[45,46]. CartoDEM is derived from stereoscopic imagery from the Cartosat mission and is available in the public domain at a 30 m × 30 m grid resolution. The vertical datum for CartoDEM is WGS84, i.e. the heights available from CartoDEM are ellipsoidal heights. DEM (or DSM) with ellipsoidal heights has limited usage because it does not follow the water-flow criterion. All the satellite imageries derived from DSM have ellipsoidal heights, but a few of them have been further referenced with respect to a global geoid model (e.g. EGM96) to provide the required physical (orthometric) heights for various applications, e.g. flood mapping and management. DEMs (precisely DSMs) that are referenced to EGM96 include SRTM and ASTER, both of which are extensively used in India, although their accuracy varies primarily depending on the topographic landform and ruggedness[44]. CartoDEM as available is still referenced to WGS84, and hence the user must use EGM96 while comparing it with SRTM or ASTER in the area of interest or with other precise global or regional geoid models for various activities.

SoI in its Annual Report has mentioned that it would develop three DEMs[46]: a national DEM of ±10 m accuracy, a high-resolution DEM of ±3–5 m accuracy and an ultra-high resolution of ±50 cm accuracy. There is confusion about whether the mentioned numbers are accuracy (or precision, although both are different), or if they denote the expected resolution of the DEMs. The proposed aim to develop these DEMs is to use data from an unmanned aerial system (UAS) or LiDAR survey integrated with a precise national geoid model.

However, the present DEM that is made available by SoI is generated by digitizing the contours from the topographic maps and is available at 10 m resolution (pers. commun., 2022). SoI may have also developed DEMs with different resolutions, but we have no knowledge of the same. The following three points should be noted: (i) The topographic maps were initially developed in the Everest datum and were transformed into the WGS84 datum only after 2005. The transformation parameters were not consistent throughout the country, which resulted in an absolute shifting of the coordinates by as large as 300 m. (ii) The contour interval ranges from 5 to 10 m in the plain regions to 50 to 100 m in the undulating mountainous regions, with limited spot heights (it should be noted that contour intervals further vary depending on the terrain type and scale of the map). (iii) The height information used in the topographic maps is from IVD1909, i.e. normal orthometric heights observed more than a century ago (while Helmert's orthometric heights are measured in modernized vertical datum, i.e. IVD2009). Therefore, given these points, the DEM so generated may not provide nationally consistent, precise elevation information because it may only include archaic height information collected mainly along the roads and railways. Moreover, this DEM may also be horizontally shifted due to the non-consistent transformation of coordinates from Everest to WGS84.

In addition to the massive work of digitizing the contours and developing DEMs, SoI is continuously working towards developing a precise DEM to provide an accurate, high-resolution topographic representation. Given the many Indian landforms and other conditions, data collection and processing might take considerable time. Till then, the current practice may be continued, but with the aim of recomputation (for any pursued DEM application) once a precise DEM is made available. DEMs can also be procured from SoI, but they may be based on contours from the topographic maps.

Conclusion

According to the new geospatial guidelines, Indian users can procure geospatial (geodetic) data from SoI for their respective applications. Further, the stakeholders can collect geodetic data of any quality and resolution, but all must refer to the SoI database. Therefore, it is crucial to understand the SoI database. This article briefly explains the geodetic data (horizontal position, vertical position, gravity, geoid model and DEM), and their availability status in India. The discussions provided may also be used to collect relevant metadata while procuring this data from SoI. Given that geodetic data have been collected for decades under different scenarios, the metadata will be of critical utility to meet the objective of the new geospatial guidelines and Policy, i.e. maintaining consistency and avoiding duplication in geospatial data collection and processing. The discussions also show that, though SoI has been undertaking the tasks of geodetic data collection, processing, archival and dissemination, there is still much to do in terms of defining consistent geodetic datums, which has now also been mentioned in the National Geospatial Policy.

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