WHITE PAPER

ON

GEODETIC INFRASTRUCTURE OF INDIA

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Table of Content

Abbreviations/Acronyms

For the purpose of this paper, the following abbreviations and acronyms will apply

Abbreviation/Acronym	Description
ACP	Area Correction Parameter
APREF	Asia-Pacific Reference Frame
CD	Chart Datum
CIO	Conventional International Origin
CORS	Continuously Operating Reference Station
DEM	Digital Elevation Model
DGPS/DGNSS	Differential GPS/ Differential GNSS
DORIS	Doppler Orbitography and Radio positioning Integrated by Satellite
GNSS	Global Navigation Satellite System
G&RB	Geodetic and Research Branch
GPS	Global Positioning System
GCP	Ground Control Point
GGRF	Global Geodetic Reference Frame
GGIM	Global Geospatial Information Management
GTS	Great Trigonometric Survey
ITRF	International Terrestrial Reference Frame
IGS	International GNSS Station
InSAR	Interferometric Synthetic Aperture Radar
IAG	International Association of Geodesy

IGB	International Gravimetric Bureau
IRM	International Reference Meridian
LBS	Location based Services
MSL	Mean Sea Level
NAVD	North American Vertical datum
PNT	Positioning, Navigation and Timing
RIVD	Redefined Indian Vertical Datum
RTK	Real Time Kinematic
RINEX	Receiver Independent Exchange Format
SAR	Synthetic Aperture Radar
SLR	Satellite Laser Ranging
UTC	Universal Time Coordinated
VLBI	Very Long Base Interferometry
VRS	Virtual Reference Station
VSAT Antenna	Very Small Aperture Terminal Antenna

Geodetic Infrastructure of India

Introduction

Actual surface of the earth is highly undulating with elevation varies from about +8848m (Mount Everest) to – 429m (Dead Sea shore and surface) and undulation varies from point to point. It is difficult to define the Earth's actual surface which is required for scientific mapping i.e. the edges of adjacent maps match among themselves, sum total of area of all maps of earth should be equal to surface area of the earth etc. In order to achieve this, idea of approximation of earth by a mathematical surface was mooted as early as in the beginning of 19^{th} century. It was also decided by the geodesists at that time that the earth can be approximated by an ellipsoid, to be specific a biaxial ellipsoid as mathematical computation on its surface is easier compared to a triaxial ellipsoid. However, to define this ellipsoid which best fits in the Indian subcontinent, the work of measurement of arc distance along a meridian and a parallel was started in 1802 with base line measurement in Madras with 100 feet steel chains and subsequent distance based on triangulation. This was essential to determine the two radii of the ellipsoid called semi major axis and semi minor axis. The measurement of great arc along 78^{o} meridian started from St. Thomas Madras in 1802. In year 1818, this project was christened as Great Trigonometrical Survey with a set up to execute this project. In the year 1922, this set up was named as Geodetic Branch and finally in year 1950 it was renamed as Geodetic and Research Branch.

In addition to Great Trigonometrical Survey (GTS) which involves a series of large interlocking triangles observed over entire subcontinent, other scientific operations associated with Geodesy also started gradually with time. Systematic tidal observations for measurement of Mean Sea Level (MSL) and prediction of tide heights, leveling observations for extending vertical control, measurement of force of gravity throughout India, investigation and measurement of geo-magnetic force and declination to find the deviation of true north direction from magnetic north direction required for finding direction, solar photography and seismological study work were assigned to the Geodetic and Research Branch. We have earliest tidal observation record of Khidirpur Dock, Hugli River, 1806-27 and Sagar Island 1828-29. Leveling of Precision started in 1858 following the principal triangulation from Karachi to Attock and from Dehradun to Sironj. As early as in 1815, proposal for measuring gravity at stations of the principal triangulation was stressed, though it started by two brass pendulums in 1865 and continued till 1873 by Basevi and Heaviside. Magnetic observatory was established and observation started in 1902 in the Geodetic and Research Branch campus at Dehradun.

Thus, since beginning of nineteenth century, Geodetic and Research Branch of Survey of India is conducting geodetic surveys to meet the scientific and engineering need for the country. It is no longer doing solar photography and seismological study work but it has been continuously working on horizontal datum, vertical datum, gravimetry, tidal observations and geo-magnetic studies all these years. Each of these topics as part of geodetic infrastructure of India has been described in subsequent chapters.

1. Horizontal Datum and Reference Frame

1.1 Overview

Position of a point on the surface of the earth is determined with respect to a reference frame and a datum known as reference ellipsoid whereas the third dimension i.e. elevation is measured with reference to another datum termed as Geoid. The planimetric coordinate (x,y or φ, λ) measured on the surface of earth are reduced to reference datum with tolerable error as it is essential for making further computation possible. The reference ellipsoid was originally derived by George Everest in 1830 based on the Great Trigonometrical Survey initiated is 1802 and it was named as Everest Ellipsoid on the name of George Everest. It was subsequently updated in 1888 and then in 1956 and renamed as Modified Everest ellipsoid. To derive the Everest ellipsoid one origin was chosen at Kalyanpur, Madhya Pradesh which is roughly in the centre of India where it was assumed that there is no separation (N) between ellipsoid and geoid (i.e. N=0). The latitude and longitude of this point were determined through astronomical observation and found to be 24°07'05.48"N and 77°39' 14.75"E respectively. To define a reference frame four entities are required one origin and three axes of coordinate system. Z-axis was defined by semi-minor axis of axis of Everest ellipsoid and its extension to Conventional International Origin (CIO) i.e. the mean position of pole star between 1900-1905. The X-axis is the line joining centre of ellipsoid to the Greenwich Meridian on the equatorial plane and Y- axis by 90° anticlockwise rotation of X-axis on the equatorial plane. During 1802 to 1843, under Great Trigonometrical Survey (GTS), series of large interlocking triangles were observed over entire Indian subcontinent for creating a grid with control points in all directions. In triangulation all the three angles of a triangle were measured through various versions of theodolites starting with reading resolution of 20" to 0.1" on later days. Eleven Nos. of base lines (one side of a triangle) were measured starting with chains to inver tape and steel bands later on for precise measurement. Coordinate of vertexes of triangles were computed by solving the triangles and effecting all corrections such as refraction, curvature corrections etc. These vertexes of triangles were termed as GT stations which were used as control point for further surveying and mapping. These total 3015 nos. GT stations were well monumented underground concrete structures generally located on hills tops for easy sighting through theodolite from one station to another. The entire GT triangulation was divided into 5 zones and each zone was least square adjusted involving total 2873 nos. of stations in all in these adjustments. These GT stations provided main frame with respect to whom more triangulation/traverse stations were established throughout the Indian subcontinent for surveying and mapping. The height of GT station was provided by angular measurement (through theodolite) with respect to nearest Bench Mark whose height was derived through levelling with respect to M.S.L. The GT stations have first order accuracy of the order of not less than 1:50,000 and other triangulation stations were classified as secondary and tertiary stations with accuracy not less than 1:20,000 and 1:5,000 respectively. Though the GT stations and other triangulation stations were on high hills, they served fairly well for surveying and mapping in India and adjoining countries till the end of 20^{th} century when satellite based positioning system such as Global Positioning System (GPS) arrived.

Apart from the difficult accessibility of GT stations, the biggest difference between the earlier positioning and GPS positioning is the datum. The earlier positioning was with reference to Everest ellipsoid which is a non-geocentric ellipsoid (the centre of ellipsoid do not coincides with the centre of the earth) whereas GPS positioning is based on geocentric WGS-84 ellipsoid (centre of ellipsoid coincides with centre of the earth). Though GPS was used for base line measurement for trilateration using Differential GPS (DGPS) for elimination of errors and precise positioning, the other satellite based products such as imageries used for mapping/updation of maps were also based on geocentric datum, it was decided by India to shift to geocentric datum (WGS-84) system in early 2000s and seven transformation parameters were computed using Bursa Wolf model which helped is converting all old topographical maps of India from Everest ellipsoid datum to WGS- 84 datum with 3 to 5m accuracy. These maps were named as open series map and Defence Series Maps (DSM).

1.2 Present Status

In 2006, it was decided to establish horizontal (Planimetric) control stations using GNSS on WGS-84 ellipsoid datum and in International Terrestrial Reference Frame (ITRF) using GNSS observations. Origin of ITRF coincides with the centre of the earth. Z-axis is the line joining centre of the earth to the CIO i.e. axis of rotations of earth. X-axis is defined by a line joining from the centre of the earth to the International Reference Meridian (IRM) (Malys Stephan, 2015) which is 5.3 arc second (102m) east of Greenwich Meridian. Y-axis is defined by an axis obtained by rotating X-axis in equatorial plane by 90° anticlockwise. The project was named as Ground Control Point (GCP) library. It was initiated for setting up of precise and consistent horizontal control in geocentric coordinate system for the entire country. In Phase-I of this project 291 well monumented and uniformly distributed GCPs which are about 250 to 300 km apart were established by 72 hours GNSS observation and processing the data w.r.t. International GNSS stations (IGS) using Bernese Scientific Software 5.0. All GPS observation data were in RINEX format. After this, well monumented additional 2260 GCPs at spacing of about 25 to 30 km were observed for about 8 hours and data was processed with reference to the first phase GCPs using same scientific software. After completion of all processing entire network of GCPs was adjusted using the TBC software. The location of GCPs has been shown in fig. 1

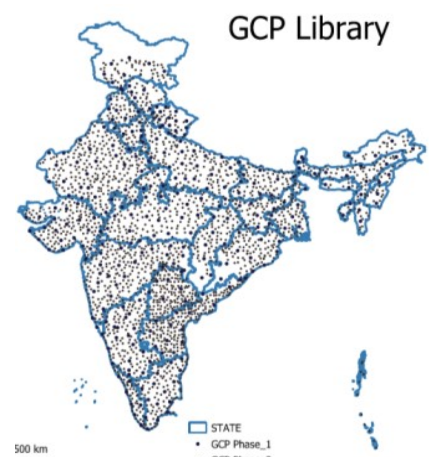

Figure 1 Schematic representation of location of GCPs

These GCPs have been coordinated in ITRF 2008 and at epoch 2005. All the surveying and mapping in India has to be done using these GCPs to keep all the maps and land measurement system consistent in the entire country. To obtain online positioning, Global Navigation satellite System

(GNSS)-based Continuous Operating Reference Station (GNSS-CORS, CORS hereinafter) have been established on total 1042 monumented points throughout India which have also been coordinated in ITRF 2008 at epoch 2005 with reference to the already adjusted GCPs. The location of CORS stations has been shown in fig. 2. In CORS measurement at the rover station is corrected by either of the following two concepts – (i) Area correction parameters (ACP), (ii) Virtual Reference Station (VRS). ACP is based on transmission of carrier phase correction requiring less bandwidth for transmission whereas VRS is based on transmission of raw phase data (Real Time Kinematics (RTK)) requiring more bandwidth for transmission. As a result of either procedures, the rover is able to determine its position in real time with an accuracy of 1 cm independent of the distance from reference station (Seeber G., 2003). Interstation spacing between reference stations influences the accuracy of positioning. Ideally it should be 50 km or less but currently SoI has established CORS station at 60-80 km interval.

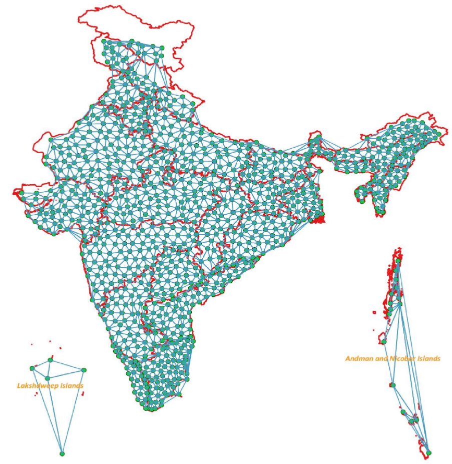

Figure 2 Schematic representation of location of CORS Stations

1.3 Path Ahead

The coordinate system of GCPs (which have replaced the erstwhile GT stations for control work) is in ITRF 2008 and at epoch 2005 (plate position 01/01/2005). As ITRF is recomputed every year, though the changes are in 1-2 cm only and due to plate motion the coordinate at epoch 2005 may not be at same position as at recent epoch say epoch 2023 and considerable time has elapsed between 2005 and 2023, it is imperative that ITRF and epoch of our coordinate system is changed for academic purpose which is possible using scientific software without changing the position of GCPs or CORS stations. All the GCPs should be connected with RIVD levelling line to provide them their orthometric height also which will be useful for geoid modelling and other engineering works. As a member of UN GGIM, India should contribute to the realisation of Global Geodetic Reference Frame (GGRF) which is possible through our GCPs and CORS. As all land records of India are being modernised in ITRF 2008 at epoch 2005 coordinate system, this system has to be maintained for ever or for a considerable time in future and for academic purposes and for realisation of GGRF, coordinate of our present GCP should be changed to dynamic coordinate system such as ITRF 2020 at epoch 2023 or some other ITRF and epoch which is possible through application of scientific software. However, this will entail fresh observations on some of our GCPs for better accuracy.

GCPs should be periodically inspected to ensure that they are intact. Apart from CORS stations, these GCPs will also be used as reference points for surveying and mapping in offline mode (Differential Global Navigation Satellite System (DGNSS)) at present as well as in future. Entire GCPs and CORS stations need to be network adjusted together for improving the accuracy of these points. In future, interstation spacing between CORS station need to be reduced for better positioning accuracy for traffic automation, auto navigation etc., and better climatic studies. Some agencies have established some CORS in some pockets of the country using public fund. They need to be integrated in SoI CORS system for their better utilisation for general good.

As and when NavIC becomes operational, the CORS GNSS receiver which are already NavIC enabled will utilise the indigenous satellite system to achieve self reliance in the area of PNT solutions catering to precision applications and LBS services in the immediate future.

2. Vertical Datum

2.1 Overview

Determination of direction and velocity of liquid flow is one of the most important tasks of engineering projects aimed for the welfare of citizens. Fixation/Identification of vertical datum is the most vital aspect in the fulfillment of this task. The task is achieved through a process known as leveling and gravity measurement and it is based on the concept that says "liquid flows from high gravity potential to low gravity potential". Vertical reference datum is the point with reference to which geo-potential (gravity potential) of all other points is determined. In order to ensure it being fairly static, the choice falls on either spheroidal level or rock cut bench mark or Mean sea level. However, most countries of the world including India have adopted Mean sea level as the datum for height. Determination of vertical datum and evaluation of heights of points with reference to it throughout the main land and elsewhere in India is a saga of utmost human endeavor and effort. While achieving this gigantic task, a number of course corrections have also taken place as the scientific knowledge has improved with elapse of time. Like elsewhere in the world, in India also initially the elevations (height) were widely determined using vertical angle measured through theodolite which was later on, since 1858, achieved through spirit leveling using leveling instruments. The leveling lines acquired during leveling operation in India from 1858 to 1909 were least square adjusted and christened as **First level Net of India** (Burrad S.G., 1920). The adjustment was constrained to Mean Sea Level (MSL) of 9 ports (four ports each in east and west coast and one at Karachi). The leveling was accomplished by leveling by two surveyors-one followed by another for same leveling line independently under practically identical conditions and normal gravity was used. This leveling was called by the name normal leveling of Precision and carried out in the form of simultaneous double leveling. About 10,000 bench marks were established in First Level Net.

However, the above system of leveling was changed to fore and back leveling from 1913-14 in accordance with the International practice at that time. Further, wooden staves were replaced by more accurate invar staves from 1929-30, normal gravity was used as usual, an arbitrary system of weighing was adopted and adjustment was constrained to local Mean sea level at four ports (two ports on east coast and two on west coast) in place of 9 ports of Pre – 1909 leveling. The leveling data accumulated from 1913-14 to 1977 was thus provisionally adjusted in 1977 but it was not used as this provisional adjustment did not differentiate between stable and unstable areas of India and due to adoption of arbitrary weighing system etc. Meanwhile the level values of first level Net (1909) continued to be used for determination of elevation.

In view of the above, it was felt that second level Net adjustment should be confined to stable peninsular India only in the first phase. In accordance with the decision of the International Association of Geodesy (IAG) made in Rome in 1954, actual observed gravity value was used in the adjustment and weighing system given by Wassef (Wassef, 1974) was used. The local Mean Sea Level of Bombay from 38 years of observation with mean epoch 1955, which is the mean epoch of leveling data under adjustment (1929-30 to 1979-80), was used as the vertical reference datum for height of India. Out of 72 level lines, 2 were found as outliers and 70 level lines (48 level lines + 22 repeated level lines) were used for adjustment.

The adjustment of this level Net was done by well known method of observation equations using Least Square technique and only one station Bombay was held fixed in the adjustment with redundancy of 37 (70-33).

In addition to the fact that whole areas of India was not adjusted in one go due to geological consideration, the time span for observations for **Second level Net** was too long, so local land movements could not be ruled out. Further, the average length of leveling line and diameters of circuits in India was 257 km and 364 km respectively whereas corresponding figures for Finland was 94 km and 160 km only. In case of Germany it was 30 km and 80 km respectively (Arur M.G. 1983). Bigger the line length and diameter, more is the error accumulation due to inherent leveling process. Due to all these reasons, the Second Level Net never saw the sun and whole exercise of many decades can be termed as futile exercise as geodetic leveling work done post 1909 till 1977 was not used for refinement of vertical datum so it was never shared to users. Nevertheless this exercise is useful for enhancement of knowledge of processes of providing vertical control and research.

In late nineteen seventies and early nineteen eighties, orthometric height was found through astro-geodetic levelling and a very coarse geoid model was developed having accuracy in meters.

Using the geodetic horizontal and vertical reference frame, a number of important project works have been completed by SoI in India and abroad. Some of these projects completed by SoI in recent past are shown in Table 2.1

Table 2.1 Some of the project works completed by SoI in recent past using horizontal and vertical reference frame

S. No.	State/Country	Name of the Project
1	Bhutan	490 MW Kholongchhu Hydro Electric (HE) Project over Kholongchhu river
2		992 MW Punatsangchhu HE Project over Punatsangchhu, Sankosh river
3		1020 MW Tala HE Project over Wangchu river in Thimpu
4		336 MW Chhukha HE Project
5	Andhra Pradesh	1670 MW Srisailam left bank HE Project over Krishna river
6		965 MW Nagarjuna Sagar Project
7	Arunachal Pradesh	1000 MW Naying HE Project over Siyom river
8	Assam	Bogibeel rail cum road bridge Project
9	Bihar	1130 MW Subarnrekha Multipurpose Project
10	Chhattisgarh	Bhilai Steel Plant
11	Delhi	Verticality of Minars of Qutab Minar
12	Goa, Daman and Diu	Tillari Irrigation Project
13	Gujarat	1450 MW Narmada Dam Project
14		Crustal movement studies in Valsad district, Gujarat
15		Gujarat Engineering Research Institute Project
16	Kerala	780 MW Idoiki Dam Project

17	Madhya Pradesh	Anpara Thermal Power Station Survey
18		425 MW Ban Sagar Project
19	Maharashtra	600 MW Koyna Dam Project I and II
20		320 MW Koyna Dam Project III
21		1000 MW Koyna Dam Project IV
22	Manipur	105 MW Loktak HE Project
23	Himachal Pradesh	800 MW Kol Dam Project in Bilaspur
24		800 MW Parbati HE Project Stage II over Sainj river, Kullu
25	Jammu and Kashmir	390 MW Dul-Hasti HE Project over Chenab river, Kishtwar
26		480 MW Uri Hydel Project
27	Karnataka	300 MW Gundia HE Project over river Gundia
28		Vijaynagar Steel Plant
29	Meghalaya	Umkiten Reservoir Survey
30	Mizoram	Karnaphulli Reservoir Survey
31	Nagaland	Jhansi Dikhow Project
32	Odisha	600 MW Upper Indravati Project
33		Gopalpur Port Survey
34	Punjab	1325 MW Bhakra Dam Project
35	Rajasthan	Udaipur Aerodrome Survey
36		50 MW Mahi Bajaj Sagar Project-I
37		90 MW Mahi Bajaj Sagar Project
38	Uttarakhand	420 MW Tiuni Plasu HE Project over river Tons, Dehradun
39		520 MW Tapovan Vishnugad HE Project
40		400 MW Koteswar dam Project
41		444 MW Vishnugad Pipalkoti HE Project
42	Uttar Pradesh	Study of verticality of Minarates of Taj Mahal, Agra
43		Rihand dam Deformation Studies in District Sonbhadra
44	West Bengal	Durgapur Steel Plant

2.2 Present Status

The leveling data of first level net which is more than 100 years old is still in use. During this period most of the Bench marks have been destroyed/ disturbed due to plate tectonics and developmental activities. As normal gravity has been measured (easily calculated mathematically) while doing leveling, this gravity cannot provide correct geo-potential as it is different from actual gravity which is essential to determine the direction and velocity of liquid flow. The mean sea level of 9 ports have been assumed at same elevation (0.000) while doing adjustment which have been proved incorrect due to different heights of mean sea level of east and west coast due to different salinity of sea water. The modern leveling has to be in terms of geo-potential numbers as it actually decides the liquid flow. The height given by first level cannot be used for scientific study like sea level rise etc. as it is based on assumption of average height of mean sea level of 9 ports being same.

The instruments used for leveling for First Level Net were not sophisticated as they are today. Even forward and back leveling required for high precision leveling was unknown at that time. Therefore, revision of Indian vertical datum needs to be carried out as has been done elsewhere in the world. Identical to India, a "mean sea level" reference surface was determined in 1900 by holding elevations fixed at five tide stations in USA. Two other tide stations added in 1903, one more in 1907 and one more in 1912 and readjustment was done (Berry, 1976). The next general adjustment of the vertical control network was conducted in 1929 when 21 tide stations of USA and 5 tide stations of Canada were held as fixed with leveling network 75,159 km of USA and 31,565 km of Canada. At the time of the 1929 general adjustment, the mean sea level of various tide stations held fixed at 0.0 elevation, effects of sea surface topography, water temperature, salinity etc. were ignored.

In order to overcome the limitation of level Net of 1929, USA planned to determine North American Vertical Datum (NAVD) which is also known as NAVD88. It consists of a leveling network in the North America subcontinent ranging from Alaska through Canada across the United States, affixed to a single origin point on the continent at father point/Rimouski, Quebec, Canada tidal station.

Additional tidal bench mark elevations were not used due to the demonstrated variations in sea surface topography i.e. the fact that mean sea level is not the same equipotential surface at all tidal bench marks. In fact error estimated in considering each of tide stations of Pacific and Atlantic Ocean tidal stations to be on the same elevation was found to be about 70 cm. This is similar to India where elevation difference between east coast and west coast has been found to be in the range of 40 cm due to predominantly salinity difference of water of Arabian Sea and Bay of Bengal.

The height system used in Australia is actually a modified version of the normal-orthometric height system which is being changed to Helmert orthometric height system by actually using gravity values at Bench Marks. The Australian Height datum is an amalgamation of decades of spirit leveling work conducted by numerous states and territories across the country and was corrected to align with mean sea level observations of thirty tide gauges positioned around the entire coastline.

Taiwan has also upgraded its height system based on geo-potential number with the use of actual observed gravity.

In Japan the vertical datum has been updated with latest leveling survey data with system change from normal orthometric height to Helmert orthometric height. For leveling Japanese vertical datum, Bench Mark (BM) at Tokyo has been assumed as fixed instead of Local mean sea level of the several tidal stations.

The primary leveling net of Europe has already been adjusted in Geo potential units (GPU) and future work in Europe must clearly be done on the same system.

In conformity to the above developments world over, Survey of India also decided to change its vertical datum in 2006 and named this project 'Redefined Indian Vertical Datum (RIVD)'. The geo-potential numbers and Helmert orthometric heights have been computed taking type 'P' standard bench mark of Mumbai as a fixed point for entire leveling Network (about 19450 km) which was connected with vertical datum, the local mean sea level of Apollo Bunder Tidal observatory, Mumbai (1978-1994). A long pending requirement of applying observed gravity values to the observed geometrical heights was applied by observing gravity values at every bench mark at a spacing of 3 to 5 km. Gravity at intermediate bench marks have been interpolated as a linear function of elevation and horizontal distance. A least square adjustment method was adopted to adjust leveling network in terms of Geo-potential Numbers and subsequently Helmert orthometric heights have been computed. All the precision measurement for observing leveling sections, gravity values and computational procedures are taken into account with utmost precautions. Leveling instruments like Trimble Dini-12 and Leica DNA -03 digital levels which have reading resolution 0.1 mm and relative gravimeters CG-5 and CG-3M with reading resolution 1 μgal have been used. The skeleton of leveling lines all along coastline and in the middle of India has been completed with 29 lines, no of junctions 19 and in 11 number of circuits with maximum closing error of a circuit 0.2504 gpu and minimum closing error of a circuit 0.0010 gpu which is considered very good. This leveling skeleton is being densified through high precision leveling being conducted for Geoid modeling and for other project works. However, this RIVD leveling data is not supplied to most of the users due to non completion of densification work as well as issues of adjustment etc. The high precision leveling lines are shown in Fig. 3.

Figure 3 Schematic representation of high precision leveling lines

It is easy to find orthometric height from ellipsoidal height above a geocentric ellipsoid through geoid modelling (particularly through gravimetric) compare to an ellipsoidal height above a non-geocentric ellipsoid like Everest ellipsoid, the erstwhile mapping datum of Indian subcontinent. In 2012 onwards, a rigorous study in the pursuit of developing an accurate geoid model for India to convert ellipsoidal height to orthometric height without resorting to leveling was taken up. Hybrid geoid models of accuracy in order of 10 cm have been made available for a number of states of India recently.

2.3 Path Ahead

India an active member of UN-GGIM is duty bound to contribute to realization of International Height Reference System (IHRS)/International Height Reference Frame (IHRF). So our height system must be connected to global Mean Sea Surface (W_o). Sea surface heights have two components Geoid + Dynamic topography. Our tidal observatories have stilling wells which can minimize the marine perturbations so it is suggested that the geo-potential of Mumbai tidal observatory (W_o^L) should be computed (using the most accurate Global Geoid Model (GGM)) and all the RIVD network must be adjusted with reference to it and this RIVD leveling data should be open to users so that this scientific leveling data can contribute to the nation development. It is understood that the inherent error of leveling accumulates as one move from one point to other, but as the adjustment has been done in circuits, the error may be reduced considerably. The other option is to find sea surface topography of a number of tidal observatories at east and west coast and accordingly local geo-potential of these ports are calculated and then the adjustment is done using all these tidal stations including Mumbai. But, as sea surface topography is difficult to be calculated at the moment due to lack of study, it is better to overlook this option at present.

3. Gravity Measurement in India

3.1 Overview

Earth's gravity affects practically every geodetic measurement. The Earth's masses inside its actual outer surface are in constant motion. A full knowledge of density of such masses as it varies from point to point below the Earth's crust is impossible and so is the gravity. The understanding of Earth's gravity field, its variation and its behavior from point to point is the most difficult aspect of learning and/ or studying geodesy.

As early as 1815 when proposals for the execution of triangulation system in India were mooted, the desirability of determining the force of gravity at the stations of the principal triangulation was felt. However, this idea was executed only in 1865 with pendulum gravimeter on the suggestion of the President of Royal Society of London. Two brass pendulums were loaned by the Royal Society to the Govt. of India at that time and after calibration at the Kew observatory they were employed for work. Basevi and Heaviside used these instruments from 1865 to 1873 when gravity at about 30 stations in India from Cape camorin to Ladakh were observed. A series of observations were also made by employing Russian Repsold pattern and Katar's convertible pendulums at almost same time but these observations were rejected being not sufficiently accurate. The pendulum observations kept in abeyance from 1873 to 1903. In 1903 observations resumed with Sterneck's ½ sec pendulum which continued till 1925. Observations from 1926 to 1939 were made employing three nickel-steel pendulums. Till 1939, a total 564 pendulum stations (at a spacing of 70 miles) covering the whole of the country were available. The gravity observations remained suspended from 1939 to 1947 due to World War II. In 1947, it was felt that broad frame work for gravity observations with pendulum had already been established, it needed to be extended. For extension work two gravimeters were acquired – a Frost gravimeter in 1947 and Wordon Geodetic Model Gravimeter in 1953 which enabled the data acquisition very fast. The pendulum instrument was unsuited on account of the laborious observations and compilation. In 1948, first pendulum base station in India at Dehradun was connected to World Gravity Network. After this in series of events, more pendulum base stations were connected with World Gravity Network.

In order to conduct systematic gravity survey throughout the country, in 1959, a specialized unit was established in Geodetic and Research Branch (19 Geophysical Party). During International Geophysical year 1963, First order Gravity Station at Palam airport, New Delhi was established which was readjusted in 1969 (979.13433 gals - University of Wisconsin, 1969). In 1965, one Lacoste and Romberg Gravimeter G-84 and later on two same types of Gravimeter G-658 and G-749 were procured. These relative gravimeters helped in speedy coverage of gravity data in India and served for about 30-40 years. Since these gravimeters give only relative gravity measurements, their accuracy is usually significantly higher than that of absolute gravity measurements. With the advent of laser interferometer, free fall absolute gravimeters were developed by Faller in 1965, sufficiently portable and far more reliable gravity measurements became possible. The achievable accuracy depending largely on control of the instrument environment and number of repeated observations is of the order of or better than 100 mgal for pendulum and about 10 mgal for free fall absolute gravimeters (Vanicak P, 1982). It is mentioned here that pendulum and free fall are two types of absolute gravimeters used for measurement of absolute gravity.

During April to June 1971, a precise gravity network of 35 airport stations based on the first order gravity station at Palam airport, New Delhi was established through Lacoste – Romberg Gravimeter No. G-84 which was transported through air over the network of stations from Trivandrum in south to Srinagar in north, Bombay in west to Mohanbari in the east. The four stations in New Delhi, Calcutta, Madras and Bombay which were more precisely established by a large number of repeat observations were utilized as base stations for facilitating easy occupation of the remaining 31 stations within their respective zone. This network was further diversified to 56 Standard Gravity Base Stations during 1971 – 1985. Some of the projects in gravity completed by SoI in recent past are shown in Table 3.1

Table 3.1 Some of the project works completed by SoI in the field of gravity in recent past

S. No.	Indenting Agency	Year	Work
1	Metrakal Technologies, Pune	2023	Gravity points were observed using relative gravimeter
2	Gatrad Cal Test Laboratories, Ahmedabad	2022	Gravity points were observed using relative gravimeter
3	Godrej Boyce Manufacturing Co. Ltd. Mumbai	2022	Gravity points were observed using relative gravimeter
4	DVG Laboratories and Consultants Pvt. Ltd.	2021	Gravity points were observed using relative gravimeter
5	Oil India Corporation, Duliajan, Assam	2018	Gravity points were observed using relative gravimeter
6	Yantrika Instruments Ltd., Gurugram	2017	10 gravity stations observed inside weight making lab and pressure lab.
7	M/s Hemshell service centre Makar Pura GIDC estate, Vedodara	2017	08 gravity stations observed with relative gravimeter inside calibration laboratory
8	LEOS, ISRO laboratory, Bangalore	2017	01 gravity point observed using relative gravimeter

3.2 Standardization of Gravity

With the elapse of time, the reliability of gravimeters increased. An absolute reliability of about $\pm$10 mgal in 1900 has improved to better than 0.1 mgal now. In the olden days absolute gravity used to be measured through pendulum gravimeter which was less reliable. For better geodynamic study, exploration of mines and minerals and tectonic study, it is important to standardize the observed gravity values worldwide. Therefore, global standardization of gravity started as early as in year 1900 known as Vienna system. The stations with absolute gravity determination provide the anchoring points of the network while the relative measurements provide the ties between points. The establishment of global gravity networks has been coordinated internationally since the beginning of the previous century. As early as in 1909, the International Association of Geodesy

(IAG) adopted the International Potsdam gravity system, a network used for numerous tasks. It resulted in -16 mgal corrections in Vienna absolute gravity datum. When the absolute and relative observations are made and assessed for accuracy, an adjustment can be carried out using any adjustment technique (practically identical with that of geodetic leveling). In 1947 Worden High Range Gravimeter was developed which permitted gravity measurement on global basis with reliability of better than 1 mgal. In 1948, an around the World – series of 33 primary base stations as well as 150 new secondary gravity base stations were observed. However, reliability of measurement was 2 to 5 mgal. In 1959, IAG and International Gravimetric Bureau (IGB) in Paris adopted the 34 fundamental International Gravity bases which were observed through Woollard and Rose Gravimeter having reliability in the order of $\pm$0.3 mgal. Woollard and Rose (1963) brought into focus the problem of International Standardization of gravity and their possible solutions. This resulted into the International Gravity Standardization Net 1971 which incorporates a change of -14.0 mgal overall and -14.7 mgal in Indian subcontinent with respect to Potsdam system. The IGSN 71 values are on a different absolute datum from the Woollard and Rose and other earlier gravity values of Potsdam gravity system and should be significantly superior in terms of gravity standard represented as well as have a higher degree of reliability. The absolute reliability of the IGSN 71 values worldwide as defined by statistical test in $\pm$0.05 mgal (Morelli, et al, 1974). In the IGSN 71, the accuracy of gravity at any station is on average 36 mgal (Whalen, IAG, 1974). IGSN 71 is a worldwide network consisting of 24000 gravimeter, 1200 pendulum and 10 absolute measurements collected over 20 years and adjusted by a small group of special study group 5 of the International Association of Geodesy (IAG), discussed and approved within the same Association and adopted at the XV General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Moscow in August 1971.

The concept of the IGSN 71 differs from that of earlier gravity reference systems in that datum is determined not by an adopted value of a single station, but by the gravity values for 1854 stations obtained from a single least square adjustment of absolute, pendulum and gravimeter data. Standard errors for IGSN 71 gravity values are less than 0.1 mgal.

In India precise gravity network of thirty five stations based on the first order gravity station at Palam airport, New Delhi (979.13433 gals – University of Wisconsin 1969 value) was established during April – June 1971 covering the entire country, in order to use them as reference bases for any future gravity survey in India with a repeatability of + 0.05 mgal or less.

3.3 Present status

Geodetic and Research Branch of Survey of India has observed about 40,000 gravity stations since inception till date, 22637 after 1988-89 by Lacoste and Romberg (resolution 10 µgal) Scintrex CG-3M (resolution 1 µgal), Scintrex CG-5 (resolution 1 µgal) and Scintrex CG-6 (resolution 1 µgal) relative gravimeters. The above 40,000 gravity values have some data which were observed prior to last century by very course resolution instruments, whether they should be discarded or they can be improved in accuracy and used, is an important issue to be resolved. Gravity observations with latest absolute gravimeters on the old value stations can give an estimate of the difference of old and new values. If it comes constant or approximately constant for a good number of stations this difference may be applied on other stations to find the new gravity values of all old stations. This concept has been used for changing of gravity values of stations from Potsdam system to IGSN 71 system. Survey of India has procured A-10 absolute Gravimeter in 2019 and made observation on six fundamental base stations in North India, five being in Dehradun and its suburban area and one in Chandigarh. Some other organizations like National Geophysical Research Institute (NGRI), Hyderabad already have absolute gravimeters (FG-5).

3.4 The Path Ahead

The Indian gravity values are in conformity to IGSN 71 but India does not have its own domestic standardization net like other developed countries. Further, since gravity changes have accumulated due to constant deformation from 1971 to 2023 (about 52 years) and it has become possible to measure gravity values more precisely thanks to recent improvements in gravimeters, it is imperative to develop our Indian Gravity Standardization Net. This will be very useful for development of precise and more accurate Geoid model, calculation of orthometric height, calibration of weighing instruments and exploration of underground structures (Toshihiro Yahang etal, 2018). It can be achieved by establishing about 50 or more fundamental gravity points observed by absolute gravimeters and about 500 primary gravity points observed by relative gravimeters between the absolute gravity points effecting all precautions to eliminate effect of geomagnetic field, corrections like solid earth and ocean tide corrections, atmospheric pressure etc. and by adjusting the Net through least square adjustment using home grown software like SOILAP. After this all the statistical accuracy and precision assessment of the Net has to be done. Absolute gravimeters available with other domestic organizations can be calibrated through annual comparison campaign and they can also be used for this mission. By comparing our absolute gravimeters with world absolute gravimeters, our domestic gravity Net can be aligned with the World gravity Net if it is developed eventually in future. The Net can be further densified by acquiring new (usually relative) measurements.

4. Tidal Observation

4.1 Overview

India has more than 7500 km long coastline about 5400 km on the mainland and remaining on islands and about 250 million people (130 cities) are living within 50 km distance from shore. Mean Sea Level (MSL) has been used in India as datum for vertical control. Mean sea level is the mean hourly tide height for a period of 18.61 years at a tidal station. 18.61 years is the time the moon reoccupies its position exactly in universe. However, it can be obtained with 29 days tidal observations and 1 year tidal observation also but with lesser accuracy. Prediction of tidal height is required for movement of ships used for commercial purposes. It plays vital role in development of dockyard. For sustainable development in coastal region and for integrated coastal zone management, tidal data plays the most important role. Since 1877, when the job of systematic tidal observation was entrusted to Survey of India, its Geodetic and Research Branch has been continuously collecting the tidal data at a number of ports by establishing tidal observatories where the data is collected 24x7 throughout a year and thus it has a large store house of tidal data of major ports for 146 years. Apart from the time series studies, these tidal data (inclusive of storm surge, cyclone and tsunami etc.) is used to determine the highest flood line. Based on the availability of tidal observation data, ports have been classified as Primary port and Secondary port. Primary ports are the ports where tidal data is continuously observed through tide gauges or those ports that are no longer operational but having tidal data recorded for a long period say minimum 10 years. Secondary ports are located between primary ports having tidal records for at least one month period. Different water levels of sea have also been defined. Highest high water level observed in a year at port is termed as Annual Highest High Water (AHHW) whereas Highest Astronomical Tide (HAT) is defined as the predicted highest tide in 19 years period at a port.

Tidal heights are referred to locally fixed reference datum called Chart Datum (CD). It is the lowest low tide height at a place, the water level can seldom go down below it. Bathymetric contour shown on the hydrographic charts are also referred to this datum. Chart Datum (CD) varies from place to place and tide level with respect to CD also varies from place to place and increases with the increase in latitude in the context of Indian Sub-continent. CD does not vary linearly between two points. For two adjacent ports located very close to each other, this may be treated as varying linearly but for longer distances, 32 days tidal observations are imperative to determine CD and use it for determination of tide level. Survey of India (G& RB) has determined Chart Datum of 272 no of primary and secondary ports of its coastline for better estimation of tide level and its prediction till date. Annual tide is a result of small-small tides of different factors (tidal forces), such as Solar annual (Sa), Solar Semi-Annual (Ssa), Moon monthly (Mm) etc. These constituents are derived using tidal data observed at primary as well as secondary ports through different mathematical models and are used for determining/predicting the highest high tide level for 19 years at a secondary port. Application of mathematical model in deriving tidal constituents and various tidal parameters such as Chart Datum, Mean Higher High Water (MHHW), Mean Lower Low Water (MLLW) etc., is termed as tidal analysis. This tidal analysis is being carried out since 1878. From 1878 to 1921, data for tidal prediction used to be sent to England where they were used in a tide predicting machine and tide prediction tables (Tide Tables) were prepared and published. The last Tide Tables published in England were those for 1922. After this entire prediction, printing and publications of the tide tables have been carried out in India as the tide prediction machine was brought to India in 1923. In 1953, a new tide predicting machine (constructed by M/s A. Lege and Co.) which was equipped with 42 components was procured and set up in G&RB, Dehradun. G&RB publishes Tide Tables every year for 70 Indian and Foreign ports for one year advance prediction which is available in hard copy as well as softcopy form. Survey of India has responsibility to predict daily tide for 30 Indian and 14 foreign ports (lying in Myanmar, Sri Lanka, Iran, Egypt and Oman). It also publishes daily tide prediction of 26 foreign ports on sharing of data from Yemen, Iraq, Tanzania, U.K., Spain, Malaysia, China, Korea, Germany, Japan and South Africa. Survey of India shares its tidal data to Permanent Service of Mean Sea Level (PMSL), London.

Post 2004 Tsunami, the work of tidal observatories came in limelight. New organisation like Indian National Centre for Ocean Information Services (INCOIS), Hyderabad came up for development of Tsunami early warning system. In this endeavour Survey of India shared its heritage tidal data to INCOIS and Bhabha Atomic Research Centre (BARC), Mumbai and modernisation of our already established tidal observatories were taken up by DST sponsored project and a few more tidal observatories were established. In addition to conventional float type tide gauges, pressure sensor tide gauges were installed at each observatory for cross checking the data, dual frequency GNSS receivers and VSAT antenna (mesh network) with dedicated bandwidth were also co-located with these observatories for online data transmission. Some of the projects in the field of Marine Geodesy completed by SoI in recent past are shown in Table 4.1

Table 4.1 Some of the project works completed by SoI in the field of Marine Geodesy in recent past

S. No.	Indenting Agency	Year	Work
1	Shell	2010	Determination of MSL and Chart datum at Hazira, Gujarat and their connection with IMSL, Rectification of the Radar tide gauzes installed by Shell Hazira with reference to chart datum
2	ESSAR	2009	Fixation of chart datum at Hazira, Gujarat
3	RGPPL	2011	Fixation of chart datum at Ratnagiri, Maharashtra
4	ESSAR	2011	Provision of GNSS Control Point at Hazira, Gujarat
5	ESSAR	2012	Fixation of chart datum at Salaya, Gujarat
6	Integrated Coastal Zone Management (ICZM) Project, World Bank	2012-14	Fixation of chart datum all along east and west coast of India

4.2 Present Status

In collaboration with port authorities, presently Survey of India is maintaining a network of 36 permanent stations located along India coasts and Islands (30 mainland, 4 at Andaman Nicobar and 2 at Lakshadweep Island). Post Tsunami 2004, the tidal stations were equipped with pressure sensor tide gauges, VSAT antenna and dual frequency receiver at each observatory besides the conventional float type tide gauges. Data loggers were installed to convert the conventional tide gauge data in digital form for online transmission. In initial days, some VSAT antenna worked but subsequently gradually all stopped working. The dual frequency GNSS receivers could not survive for more than a year or so due to salty climatic conditions at sea coasts. At present, only 23 tidal observatories are operational where float type conventional tide gauge are only working at 22 stations and pneumatic tide gauge at 01 station. Pressure sensor tide gauge are not working on any of the tidal observatory. In recent past (2011-15), Survey of India has completed World Bank funded integrated coastal zone management (ICZM) project where past as well as fresh tidal data has been used as foundation data. SoI has shared its tidal data to PMSL till 2020. Subsequent data are being processed to share.

4.3 Path Ahead

Tidal data are very important for safety and security of our coastal people for saving them from natural disasters like Tsunami, Storm surge and Cyclonic flood etc., as this data is vital for developing early warning systems. Thus it is important also for having our vital installations such as nuclear power plants which are mostly on sea shores. Therefore, it must be ensured that at least two types of tide gauges are working on each tidal observatory at all times. For online data transmission, broadband/GSM/GPRS and Internet can be used. So, all tidal observatories should be equipped with these transmission facilities also. In the recent proposal of modernisation of tide gauges one additional Radar sensor tide gauge and one dual frequency GNSS receiver has been proposed at each tidal observatory besides the conventional float type tide gauge and pressure sensor tide gauge. Survey of India does not have permanent manpower to man all these tidal observatories. Therefore, trained manpower should be hired and in collaboration of INCOIS and port authorities a robust system of manpower management should be developed to collect tidal data uninterrupted. Survey of India has to keep on measuring MSL continuously at all primary ports for vertical reference frame.

5. Geomagnetic Survey

5.1 Overview

For accurate orientation of hard copy map in the North South direction of a place declination at the place is required. Declination is the angle between magnetic north and true (geographical) north. Maps are approximately oriented through magnetic compass which is always aligned in the magnetic North-South direction and then they are correctly oriented in true North-South direction by applying declination of the place. In order to find declination, first magnetic survey by Survey of India was undertaken in the year 1901 to 1913 throughout the country and this work was entrusted to Geodetic and Research Branch. As magnetic instruments measure geomagnetic elements – Declination, Horizontal and vertical Intensity, dip etc., though declination was needed for mapping needs, it was thought prudent to record other elements also - Declination, Horizontal force and Vertical force with SoI pattern magnetometer and dip observed with dip circle. Apart from declination chart, survey of India used to publish isomagnetic charts of Horizontal Intensity and vertical Intensity. Practice of publication of isomagnetic chart discontinued after 1995. However, SoI continued to share the Horizontal and vertical intensity data to Indian Institute of Geomagnetism (IIG), Mumbai for publication of isomagnetic charts-by IIG. Measurement of geomagnetic elements is important for study of solar flare, solar storm, climate change etc. There is strong evidence to suggest that abnormal geomagnetic variation is precursor of earthquake.

In order to observe geomagnetic elements 24x7 throughout a year in North India, calibration of field mapping instruments like magnetic compass, a magnetic observatory was established in Geodetic and Research Branch compound at Dehradun in 1902. It functioned in this complex from1902 to 1943. In 1943, this underground observatory went out of action due to flooding of underground chambers. Consequent to the resolution passed by the geophysical committee in 1947, it was decided to restart the observatory at a place having no electrical or industrial disturbance. A place 30 km away from Dehradun known as Sabhawala was chosen and the geomagnetic observatory was commissioned here in January 1964 coinciding with the start of international Quiet Sun Year after construction of buildings, procurement of instruments, their tests and trials etc. Besides studying the secular changes in the earth magnetic field, this observatory being the only one in the northern region helps in controlling the field magnetic survey in the northern part of India. The Sabhawala geomagnetic observatory has following magnetometers functional at present: (1) Askania Variograph – used for continuous graphical recording of Horizontal intensity (H), Vertical intensity (Z) and Declination (D) Components of geomagnetic field; (2) Digital Fluxgate Magnetometer (DFM) (resolution 0.1 nT H,Z and 0.01'D) for continuous digital recording of H, Z and D; (3) Quartz Horizontal Magnetometer (QHM) – Conventional Absolute Magnetometer (having precision $\pm$5nT(H) and$\pm$1(D)used for observation of absolute value of H, D at the instant of observation; (4) Magnetometric Zero Balance (BMZ) – a conventional Absolute Magnetometer (precision $\pm$5nT) used for observation of absolute value of vertical intensity (Z) at the instant of observation; (5) Total Force Magnetometer (TFM)/ENVI MAG Digital Absolute Magnetometer (resolution 0.1 nT and precision $\pm$1nT) used for observation of absolute value of Total Intensity (F) of geomagnetic field at the instant of observation;(6) Declination Inclination Magnetometer (DIM)/ MAG-01 H – Digital absolute Magnetometer used for observation of absolute value of Declination (D) and Inclination (I) of Geomagnetic field at the instant of observation having resolution of 0.1 nT for D and 1" for I. Instruments mentioned in sl. no. 3 to 6 are field instrument whereas 1 to 2 are observatory instrument.

Positional Astronomy is branch of astronomy which is of considerable interest to geodesists. In G&RB, Survey of India, positional astronomy is practiced for precise determination of positions (φ, λ) and azimuths at various stations of the horizontal control network. G&RB undertakes projects for determination of true North/Re-alignment of true North marking by star azimuth and angular measurement with Traverse. Some of the projects in Geomagnetic field completed by SoI in recent past are shown in Table 5.1

Table 5.1 Some of the projects completed by SoI in Geomagnetic field

S. No.	Indenting Agency	Year	Work
1	Indian Navigation Co. Pvt. Ltd., Gurugram	2023, 2022, 2020, 2017, 2016, 2013	Compass calibration at Sabhawala
2	HAL, Korwa	2015	Magnetic and True North marking, Azimuth observation
3	NGRI, Chhotupal, Hyderabad	2014	Magnetic and True North marking, Azimuth observation
4	Airports Authority of India, Safdarjung, New Delhi	2012	Magnetic and True North marking, Azimuth observation
5	HAL, Nasik Division	2011	Determine the variation of Geomagnetic declination of compass swinging area
6	Indian Navigation Co. Pvt. Ltd., Gurugram	2011	Magnetic and True North marking, Azimuth observation
7	Ship Centre Naval Base, Godavari Gate	2011	Magnetic and True North marking, Azimuth observation
8	HAL Avionics Division, Korwa	2008	North alignment
9	Garrison Engr. (I) AF No. 1	2005	North, South marking, GNSS observation
10	U S Library of Congress	2002	Magnetic data supply

5.2 Present Status

Survey of India (Geodetic and Research Branch) is maintaining Sabhawala geomagnetic observatory near Dehradun which is the only observatory – in entire North India to control field geomagnetic Survey in Northern part of India and used for calibration of geomagnetic field instruments like magnetic compass. Geomagnetic surveys are carried out at 178 repeat stations (Mishra U.N., 2016) which have been established approximately 200 km apart approx. throughout India. The geomagnetic data have been well archived in digital form. The magnetic survey of the country is being repeated every five year and the data are reduced for preparation of geomagnetic charts of the country. The latest Declination chart of epoch 2020 was published in the year 2021.The geomagnetic data observed at the observatory and its analysis is compiled in the form of annual observatory bulletin. The annual bulletins from 1964 to 2018 have already been published and that of 2019 is presently in the process compilation. IIG and Wadia Institute of Himalayan Geology (WIHG) have started new geomagnetic observatories in Gulmarg, J&K and Ghuttu, Uttarkashi, Uttarakhand respectively recently.

5.3 Path Ahead

Existing system of geomagnetic survey and maintenance of Sabhawala Geomagnetic Observatory which is the lone observatory in North India of its type should be maintained as geomagnetic data is important for various researches on topic affecting human life besides the preparation of declination chart once in a five year. The next Declination chart is due for preparation in 2025. Magnetic data of repeat stations is useful for study of temporal change/reversion of magnetic pole and magnetic equator.

6. Geodetic Astronomy

6.1 Overview

Astronomy is one of the oldest sciences in existence and geodesy developed hand in hand for long time. Positional visual astronomy plays a certain role in geodesy. By measuring altitude (angle above horizon) of a celestial body with time and using celestial ephemerides, latitude and longitude of a point can be computed. Another part of astronomy, celestial mechanics, is also needed in geodesy to study the satellite orbits. Ranges of Lunar Laser Ranging (LLR) of geodesy is used for computation of the orbit of Moon while astronomy is used for monitoring the rotation of the Earth. By observing multiple stars from different locations, a clean picture of wobbling of the Earth's axis of rotation can be obtained.

By measuring altitude (angle above horizon) of Polaris with time latitude of a place and by measuring altitude of East and West stars with time longitude of a place can be measured. These are known as natural latitude (Φ) and natural longitude (Λ). Natural latitude and longitude and geodetic latitude (φ) and longitude (λ) measured through geodetic instruments provide deflection of vertical which is the direction of the Earth's gravity. Its components are used to determine the difference of geoid undulation (separation between geoid and ellipsoid) between two points. Thus geoid undulation can be calculated at a number of points and using geoid undulation of several points by this astrogeodetic method, geoid model can be developed for a local area or a region. First geoid model of India was developed in nineteen eighties was an astrogeodetic model using deflection of vertical, but it was very coarse in accuracy, accuracy varying in meters.

Geodetic astronomy is also used to observe azimuth for controlling the azimuths of geodetic triangulation, traverse and trilateration. Azimuth, the angle between North and a celestial body in observer's horizon is required at satellite launching sites, Radar installation etc. Astronomy is used to observe time also. This is generally done in fixed astronomical observatories and the results are broadcast by wireless time signals. In India, geodetic astronomy is being used since the time of great trigonometrical survey (1802-1843). Some of the projects in astronomy completed by SoI in recent past are shown in Table 6.1

Table 6.1 Some of the project works completed by SoI in the field of astronomy in recent past

S. No.	Indenting Agency	Year	Work
1	Hindustan Aeronautics Ltd. (HAL), Bengaluru	2018	Marking of True North using T-3 theodolite
2	SDSC, ISRO, Sriharikota	2018	North marking station along with angular measurement
3	Hindustan Aeronautics Ltd. (HAL), Korwa	2014	Azimuth observation at 13 points
4	INS Dega, Vizag	2017	Marking True North on 2 test benches
5	Ship Building Centre, Godawari Gate Naval Base Port, Vizag	2011	Verification of Geodetic North
6	Airforce Station, Uttaralai, Barmer and Bidar	2009	Marking of True North and South of Airforce station
7	Aryabhatta Research Institute of Observational Science (ARIES)	2012	True North marking for Radar installation
8	BEL Kotdwara, Pauri, Uttarakhand	2017	Azimuth observation of 7 points from True North
9	IGI Airport, New Delhi	2011	Azimuth observation and North marking
10	LEOS-ISRO, Govt. Of India	2008	Azimuth observation and North marking
11	HAL, Aircraft Division, Nashik	2015	Azimuth observation and North marking

6.2 Present status

Survey of India (Geodetic and Research Branch) carries out project specific astronomical observations through T-2 and T-3 theodolites as and when the work is indented by any agency. This is the only organization in the country which does field work in astronomy and it has know how and expertise to find position and azimuth through astronomical observation and processing. However this branch has not been used for geoid modelling in India as much as it should have been.

6.3 Path Ahead

T-2 and T-3 theodolite which are used for astronomical observations have become obsolete and observation through them is quite cumbersome. In modern days and in most of the developed countries astronomical camera are being used for astronomical observation which have GNSS system built in it for very precise time measurement and to find the geodetic c coordinate of a point also instantaneously. The manipulation and citing of star through camera is very easy and have better precision.

With the use of Stellarium software, identification of stars and finding their coordinates have become easy. GNSS time can be used to observe UTC time very accurately. With all these facilities available now and by using astronomical camera the actual potential of astronomical method for geoid modelling can be explored in India also like other developed countries like USA where gravimetric geoid model is being validated through astronomical geoid modeling (National Geodetic Survey, 2013).

7. Usage of Geodetic Space Techniques

7.1 Overview

Since early 2000, Survey of India has adopted GNSS for positioning services/ground control work. Using GNSS, precise coordinates of control points have been determined by trilateration where accurately measured baseline/sides of triangles are used. This technology has enhanced the accuracy of our positioning system substantially. However, as the country progresses we require more accurate coordinate for precise engineering and scientific works. This necessitates adoption of more advanced geodetic space techniques for achievement of far more accurate baseline measurement and derivations of coordinates. A vast tract of the country is inaccessible due to difficult hilly terrain and forest etc., where terrestrial gravity measurement and bare earth mapping is difficult. We require accurate measurement of elevation of sea surface for better estimation of sea surface topography and geoid. Solution of these problems can be found by usage of Radio-astronomy and satellite laser systems. Radio-astronomy systems place a high demand on instrumentation, nevertheless mobile systems capable of achieving accuracies at a level of a few centimetres may be available in future but because of dimensions and high cost of the necessary equipment such as Very Long Baseline Interferometry (VLBI) at present, they have not been established in our country. On the other hand, radio interferometric tracking of GNSS satellites, where because of much stronger satellite emitted signals, the equipment are considerably simplified hence in routine use at present. However, for better derivation of datum, study of earth observation systems, polar motion, ITRF etc., adoption of the radio-astronomy techniques is inevitable.

Brief description of important and relevant radio-astronomy and satellite laser systems is given below:

7.1.1 Very Long Baseline Interferometry (VLBI): It is a technique of radio-astronomy which uses signals (emitted by extragalactical bodies, called quasars), that are periodic over a wide range of radio frequencies from a few MH_z to several GH_z. The quasar signals are many times weaker than satellite signals thus more complex receivers and much longer directional antenna (dishes) are used to receive them. As quasars are being very far away, they are virtually dimensionless in the sky and thus particularly suited as reference point. VLBI is one of the most accurate observation techniques in geodesy (Seeber G., 2003). Besides determination of earth orientation parameters (Precession and nutation), VLBI's main contribution are establishment and maintenance of International Celestial Reference Frame (ICRF) and International Terrestrial Reference Frame (ITRF).

7.1.2 Doppler orbitography and Radio Positioning Integrated by Satellite (DORIS): The system is based on the measurement of Doppler shift in radio signals transmitted by ground beacons and received by satellite passes overhead. A receiver onboard the satellite receives the signal and measures the Doppler shift over a short count interval i.e. 10 seconds. The ground beacons are also equipped with stable oscillators and sensors to provide in situ meteorological data. The network of beacons distributed evenly around the globe, half of the stations are on ocean islands. The DORIS onboard receiver has been installed on seven satellites and it is planned to be flown on more.

DORIS is primarily an orbit determination system but it also contributes to studying of other geodetic and geodynamic problems. Once the satellite trajectory is known, the exact position of a DORIS station anywhere in the world can be calculated. More satellite passes are used for better positioning accuracy. The permanent beacon network delivers high precision 3D coordinates for geodetic and geodynamic application. Position and motions are available to better than 1cm and 1mm/year. Due to the dense and homogeneous global beacon network, DORIS significantly contributes to the realization and maintenance of ITRF.

7.1.3 Satellite Laser Ranging (SLR): For determination of distances in satellite geodesy, the propagation time of an electromagnetic signal (mainly laser light to achieve signal strength and quality) between a ground station and a satellite is measured. A short laser pulse is generated in the ground station, and is transmitted through an optical system to satellite. The target satellite carries appropriate retro-reflectors. The reflected pulse is received at the ground station. The two way travel time (two way ranging) provides the distance. Though the cost of building and maintaining the ground segment is significantly high, this system has very high accuracy potential and hence used for precise orbit determination of satellite, absolute geocentric coordinates and can contribute significantly to ITRF derivation and estimation of crustal deformation and can be used for study of polar motion and variation of earth rotation etc.

7.1.4 Satellite Altimetry: In satellite altimetry the satellite is used as a moving platform for a sensor which transmits microwave pulses in the radar frequency domain to the ground and receives the return signal after reflection at the earth's surface. Satellite altimetry can be used to determine the geoid over the oceans as it measures distance from satellite to ground and reflective properties of water makes this method more suitable especially over the oceans. The mean sea surface can be measured by altimetry with about 1 cm precision. Although the problem of separating geoid and mean ocean topography is not yet completely resolved and remains area of the challenging scientific task in marine geodesy, the wealth of data from satellite altimetry provides the best overall approach for determination of the marine gravity field and sea surface topography (Seeber G., 2003). This will help in removing the discrepancies of height systems when they are connected due to they are tied to different tide gauges.

7.1.5 Airborne Gravity Measurement (Gravity Field Mission): The motion of a satellite is governed by its own kinetic energy and the forces that act on it. In the vicinity of the earth, the predominant forces acting on the satellite is the earth's gravitational pull and the satellite responds by following an orbit that reflects the shape of the gravitational pull. The non-gravitational part of the orbital perturbation consists of perturbation due to air drag, electromagnetic forces, solar radiation pressure tidal forces and relativistic effects and these are needed to be modelled to find the orbit that reflects the shape of the gravitational pull only. The precise orbit of the satellite is determined through data of GNSS receivers onboard the satellite at the level of 1cm level. The satellite also has gravity gradiometer which can measure the change of the gravity acceleration in space i.e. the gravity gradient. This further improves the gravity estimation. Based on those broad ideas the challenging Mini satellite pay load for Geophysical Research and Application (CHAMP), Gravity Recovery and climate experiment (GRACE) and Gravity field and steady state ocean circulation explorer (GOCE) are operating successfully and providing gravity data for geoid modelling and other geodetic studies.

7.1.6 Interferometric Synthetic Aperture Radar (InSAR): InSAR is a satellite borne radar (radio detecting and ranging) technique which is used for geodynamic deformation studies, determination of satellite orbits etc. One problem encountered by radar techniques is the low resolution of microwaves. For satellites at a height of about 800 km a several hundred meter long antenna would be required which is not feasible technically. However, when the radar measurements are taken from a moving platform (satellite or aeroplane) then the reflected signals along the flight path can be collected and combined. The aperture is hence created synthetically during the signal processing. Therefore, this technique is called Synthetic Aperture Radar (SAR). As a consequence, the radar achieves a high resolution in the along track direction. A SAR transmitting antenna illuminates the earth surface and the return signals are recorded with respect to intensity and phase. SAR interferometry (InSAR) hence offers the possibility to use the stereo effect. It is thus obviously a powerful method to map topography and to generate Digital Elevation Model (DEM). This technique is very useful for earth surface deformation mapping for landslide prediction.

7.2 Present Status

Indian Subcontinent has no VLBI or DORIS station as on date. ISRO is in the process of installation of two SLR stations one at Ponmudi, Kerala and another in Mount Abu, Rajasthan to track NavIC and other satellites. ISRO along with French National Centre for Space studies CNES has recently launched a satellite mission SARAL (Satellite with ARGOS and ALTIKA) for oceanographic studies. SARAL performs altimetric measurement designed for study of ocean circulation and sea surface elevation.

Due to non availability of any DORIS station in Indian subcontinent, this part of world is not able to contribute in realisation of ITRF and other geodetic studies and research work besides further refinement of coordinates. After more than thirty years of operation, DORIS has developed into one of the key technologies in geodetic space techniques.

7.3 Path Ahead

Survey of India plans to install and use above explained systems in near future. As no other satellite geodetic technique provides all fundamental parameters to determine terrestrial reference frame, earth observation parameters etc., it is desirable that two or more systems (instrument/technique) are located at very close locations for comprehensive studies. More aggressive use of LiDAR (Light Detection and Ranging) technique which is a comparatively low cost technique should be used for creating accurate bare earth surface topographical data set in the form of DEM which will be useful for surface deformation studies and geoid modelling also. India should have its own gravity mission satellite for airborne gravity measurement. Survey of India should collaborate with institution of eminence in the field of geodesy for in-depth learning about various geodetic techniques for improving the geodetic infrastructure and research in the field to solve human centric and climatic problems. Young officers and staff of Survey of India should be sent for advance courses in geodesy in Domestic and International institutions for capacity building. Survey of India should also conduct outreach programmes to make the common masses aware about the geodetic products and services.

Conclusion

Through its Geodetic and Research Branch, Survey of India has met the geodetic infrastructure need of the country very well since early nineteenth century till date be it horizontal control, vertical control, gravity, tidal data or astronomical and magnetic measurements. Its work ethics for quality and accuracy of data is unparalleled. It has kept on improving the quality and accuracy by adopting worldwide best practices and contemporary best available technologies. However, it has hardly any exposure to space based high end geodetic techniques except GNSS. To establish India a significant entity in the comity of nations in the field of geodesy, Survey of India should venture into the space based geodetic techniques besides giving huge impetus to capacity building through offering courses in the academic institutions of high repute and emphasis on research. As Geodesy is an earth science, important for study of the earth and universe, it should be included in academic curriculum of secondary school onwards.

Considering the importance of geodetic infrastructure National Geospatial Policy, 2022 has set the time bound goals for their upgradation /modernisation to maintain positional consistency and avoid duplication. It has laid emphasis on innovation, standard and capacity building to make India global leader in this field.

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