Towards The Modernization Of Indian Vertical Datum

Dr. S. K. SINGH

KEYWORDS:- geo-potential value; tide gauge; vertical datum; GNSS/ Levelling BMs; Global geo-potential Model.

SUMMARY:-

A National vertical datum has been providing the reference frame for a variety of practical applications, for example, navigation, building of roads and other infrastructure and variety of developmental activities in the country. Many scientific studies require a precise knowledge of not only horizontal position but also the vertical position of point on the earth's surface as well as in the space. The situation regarding vertical positioning is not as advances as that of modern space based horizontal positioning. This is likely due to the fact that there is no conventional global vertical datum in reference to which a local vertical datum can be realized in a country. In India the 3D geodetic datum has already been established in relation to ITRF 2008. Clearly a similar approach is needed for the new vertical datum realizations. The present Indian vertical datum refers to Mean Sea Level which was determined more than a century ago. Over the period of time it has been realized that the local mean sea level is usually departed from the geoid, which should be the local datum surface for height, due to the effect of sea surface topography. For the sake of establishment of local vertical datum, one has to investigate the geometrical relationship between local vertical datum and the geoid. In order to achieve this objective, it is necessary to compare the geo-potential of the geoid with that of the local Mean Sea Level defining the local height system. The Indian vertical datum(IVD) was realized over a century ago in 1909 on the basis average MSL of nine tide gauge station with the assumption that Mean Sea Level measured at each of these nine observatories represents the same water level. However, later on this concept was found to be incorrect while performing the fresh adjustment of level network of India during 1977-1983 and a difference of about 35 cm was reported between Mumbai(west coast)i and Chennai(East coast) tide gauge stations with west coast being lower than the east coast. A concept for the definition of a global vertical datum has been evolved in recent times. This concept suggests that a (conventional) Mean Sea Level (and geoid) be uniquely specified by adopting a geo-potential value W_0 which best represents the Mean Sea Level in global sense. Once a conventional W0 is adopted for global vertical datum the individual vertical datum at regional, national or continent level can be related to the adopted W_0 by means of a global gravity field model, precise ITRF positions and leveled heights, which must allow a proper transformation into the corresponding geo-potential number. In order to implement the above approach of realization of modern vertical datum for Indian subcontinent a project was initiated in 2006-07 by Geodetic & Research Branch of Survey of India In the present scenario, it has been planned to define the Indian Vertical Datum in terms of geo-potential value W_0(LVD)at eight numbers of tide gauge observatories located four each on east and

west coast. GNSS observations at all the eight tide gauge bench marks have been done. The height differences to be computed from the ellipsoidal (h), orthometric (H) and geoid (N) heights will be adjusted in order to estimate the geo-potential value. In principle the residual part of the height differences correspond to the offset between the geo-potential value used in the selected Global geoid model and the local geo-potential value W_0(LVD). Apart from this approach the computation of W_0(LVD) will also be carried out using the methodology based on Molodensky theory.

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1. INTRODUCTION –

The primary component of any vertical reference system for physically meaningful heights is an equipotential surface of Earth's gravity field, which represents what is commonly called as a vertical datum. Regardless of the particular type of physical heights within a vertical reference system, the underlying vertical datum defines an unequivocal zero-height level relative to which terrestrial vertical positions can be obtained by geodetic levelling techniques. In geodetic theory the rigorous definition of a vertical datum adheres to the fundamental equation:

$$W(x, y, z) = W_0$$

which specifies a single equipotential surface of Earth's gravity field in terms of a reference geopotential value. However, the terrestrial methodology that has been followed in practice for the realization of most vertical datums neither incorporates a priori value for W_0 nor does it entail a gravity field model $W(x, y, z)$ for their spatial representation. Instead of a virtual realization scheme as suggested from the fundamental definition, the establishment of vertical datum has been commonly based on a more tangible approach by constraining one, or more terrestrial stations to be situated at known vertical distance from an unknown reference equipotential surface. From a practical point of view the adoption of such origin points with unknown gravity potential, has been sufficient for setting up local vertical datums (LVDs) over a regional or continental scale via terrestrial levelling techniques. In most cases, the established 'crust fixed' LVDs refer to the long-term average of local Mean Sea Level (MSL) that is observed at one, or more, tide gauge stations which are vertically tied to their corresponding origin points(T. Hayden, E. Rangelova, M. G. Sideris and M. Véronneau,2012)

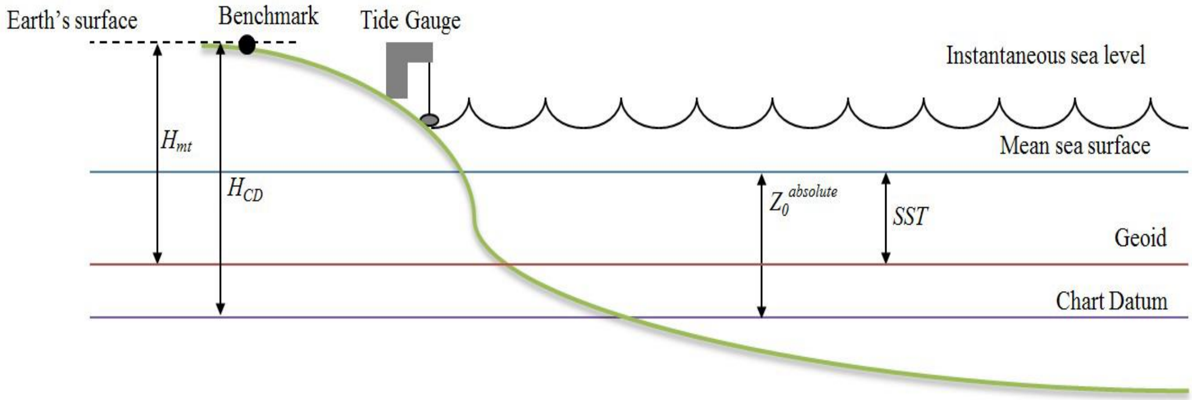


Fig.1. Relationship between various heights at Tide Gauge station

The origin point of a tide gauge station is termed as Chart Datum (CD) (Fig 1), which is a point below the lowest low water observed for sufficiently long period (minimum 18.5 years) at that particular tide gauge stations. However, the relationship among the CDs of tide gauge stations involved in setting up of a local vertical datum has been largely unknown which resulted into the systematic distortion in measurement of MSL at the tide gauge stations. In the presence of such distortions, one may question the rationale of aligning the average MSL of these tide gauge stations with LVD. Further, the fixed origin points, in such cases, realize a zero-height level that is not theoretically matched to a single equipotential surface due to combined distorting effects of MSL measurements and Sea Surface Topography (SST).

The Indian vertical datum(IVD) was realized over a century ago in 1909 on the basis average MSL of nine tide gauge station namely Karachi, Karwar, Bombay, Beypore, Cochin, Nagapattinam, Madras, Vishakhapatnam, and False point with the assumption that the Mean Sea Level at all these stations represent the same level surface.

Evidently, the incorrect assumptions lack of a reference geopotential value, non incorporating the effect of sea surface topography and solid earth's tide in establishing not only the Indian Vertical Datum but other contemporary datums as well does not prohibit the precise determination of vertical position through relative measurements from existing bench marks. However, with the extensive use of satellite technology in the field of surveying and mapping and other scientific and non scientific applications requiring knowledge of vertical positions of a point in terms of geopotential value, the current terms vertical datum has lost its significance where even the height of existing BMs above MSL does not match with the recently determined MSL of Indian Coast. In short the existing vertical datum of India suffers from distortion arising out of sea level variability, crustal deformations and inconsistence with the recently established National Geocentric Reference Frame (NGRF). Over the past 5 years Survey of India has physically surveyed many control marks to determine their coordinates and ellipsoidal heights in terms of NGRF, but due to lack of relationship between NGRF and IVD, it has been difficult for users to consistently integrates GNSS observations with IVD based height and they have to resort to adopt the time consuming and expensive techniques of geodetic levelling in order to get the precise height information.

In order to overcome the limitations of existing vertical datum and considering the cost of maintenance of levelling networks it has been decided to redefine the Indian Vertical Datum to make it compatible with GNSS technology and also to meet the users requirement for scientific and non-scientific applications. The main objectives of redefining the Indian vertical datum are:-

(i) To provide a reliable frame for consistent analysis and modelling of phenomena related to the Earth's gravity Field (e.g., sea level variations from local to global scales, redistribution of masses in oceans, continents and the Earth's interior etc.).

(ii) To allow the reliable combination of physical and geometric heights in order to explore the maximum advantages of satellite geodesy.

(iii) To develop a height system to a defined accuracy that enables the generation of orthometric height from ellipsoidal heights.

(iv) To support multiple vertical datums and authoritative transformations of heights to an acceptable and defined accuracy.

(v) The new vertical datum will use geoid as reference surface rather than the conventional Mean Sea Level measured at Tide Gauge Stations.

2. APPROACHES AND STRATEGIES FOR DEFINITION AND REALIZATION OF INDIAN VERTICAL DATUM:-

Height (vertical) datum is a reference surface of zero elevation that geometrical or physical heights of points on the Earth are referred to. It can be defined by: observing the sea level, gravimetric geoid determination or the selection of reference ellipsoid (e.g. GRS80). Defined by observing the sea level and geoid datum relates to the reference surfaces for the gravity-related heights (geopotential, dynamic, orthometric, normal heights) whereas ellipsoid is the reference surface for the geometrical heights (ellipsoidal). A reference system consists from reference surface (height datum) and origin points with known height from which heights of all other points are calculated. Currently, there are more than one hundred different height reference systems worldwide that are inconsistent to each other. Generally, two different approaches of height datum and reference systems exist(Matej Varga, Olga Bjelotomić, Tomislav Bašić,2016).

2.1 MSL/Levelling based height reference system:-

Traditionally, tide-gauges have measured sea level over a longer period. These data are averaged in observation epoch to provide the value of the MSL as a zero reference surface (height datum origin). A levelling-based height reference system is realized by means of precise levelling at connected geodetic points (benchmarks) and the establishment of precise levelling networks over the territory. Until GNSS era, the MSL/levelling height reference system was the only possible option to use physical heights over some country or continent. Therefore, most of the height reference systems throughout the world are defined and realized in this way.

2.2 GEOID/GNSS based height reference system:-

The alternative approach in defining a height datum is my means of gravimetric geoid. The gravimetric geoid is an equipotential surface that is determined from the measurements of the Earth’s gravity field and serves as a reference surface for the most physically meaningful orthometric heights (in terms of traditional geodetic glossary: *heights above sea level*). A geoid-based height datum would be defined solely by calculating the high-resolution gravimetric geoid model from satellite, airborne and terrestrial gravity data. If gravimetric geoid model should be adopted as height datum, its absolute vertical accuracy should be at the order of 1-2 centimetres. Height reference systems could be realized solely by GNSS surveying.

Since in Indian context the requirement of such accuracy is difficult to achieve at the moment therefore it has been decided to employ a methodology which will combine above two options in a systematic manner. The proposed methodology will utilized the MSL, GNSS, Sea surface topography and Global geopotential model information to realize the Indian vertical datum.

Under this approach integration of the 8 nos selected tide gauge stations would be carried out through high precision leveling and gravity observations. At these tide gauges the MSL heights will be reduced to geoid/equipotential surface using the best available SST model to define a national vertical datum. The difference between this geoid/equipotential surface and ellipsoidal heights derived from GPS observations, along with gravity data, would be used to derive a geopotential value for the geoid.

Such an approach would have the following advantages:

- The vertical datum established in this manner will be consistent and support the development of a precise gravimetric geoid for the country.
- It will result in a nearly true level (equipotential) datum as the long range systematic errors in the levelling will be marginalised as the entire computation will be done in gpu unit.
- The integration of the existing TG datums would bring significant improvements to the orthometric height datum.

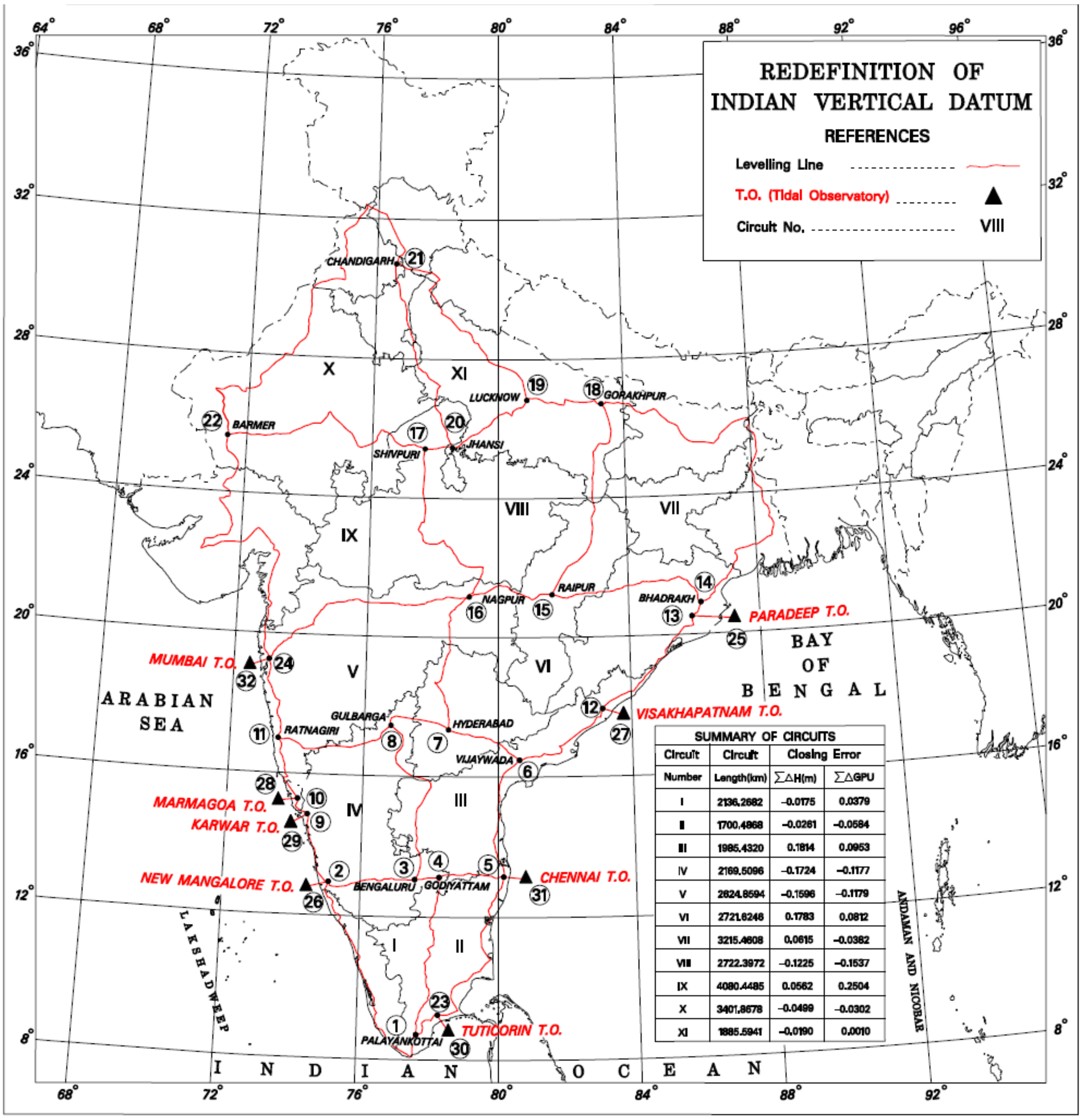
  However this approach may have the following disadvantages:
- Analysis will be more complicated because of the various and unknown distortions (eg levelling errors) incorporated into the geopotential value of geoid.

In order to achieve the above mentioned objectives following activities were planned and executed.

(i) A skeleton levelling network of approximately 500 benchmarks consisting of 29 levelling lines, 31 junction points covering a distance of 19,450 linear km was established(Fig.2)

(ii) Gravity observations on all the bench marks en-route levelling lines were carried out.

(iii) GPS Observations on 8 tide gauge stations (4 each on East and West coast) were carried out to facilitate the estimation of geopotential value of IVD.



Circuit Number	Circuit Length(km)	Closing Error ∑ΔH(m)	∑ΔGPU
I	2136.2682	–0.0175	0.0379
II	1700.4868	–0.0261	–0.0584
III	1985.4320	0.1814	0.0953
IV	2169.5096	–0.1724	–0.1177
V	2624.8594	–0.1596	–0.1179
VI	2721.6246	0.1783	0.0812
VII	3215.4608	0.0615	–0.0382
VIII	2722.3972	–0.1225	–0.1537
IX	4080.4485	0.0562	0.2504
X	3401.8678	–0.0499	–0.0302
XI	1885.5941	–0.0190	0.0010

Fig.2. Leveling Network for Redefinition of Indian Vertical Datum

3. THEORETICAL ASPECTS OF PROPOSED METHODOLOGY : –

3.1 Determination of Geopotential value (W_0^{LVD}):

The physical vertical system is defined by the gravity potential W_0 of the level surface and geopotential number C_p which is converted to height of different kinds (e.g., orthometric, normal etc.). Also there is known relationship $h - H - N = 0$ between physical heights$H$, ellipsoidal heights h and geoid ellipsoidal separation N (Ref Fig. 3).

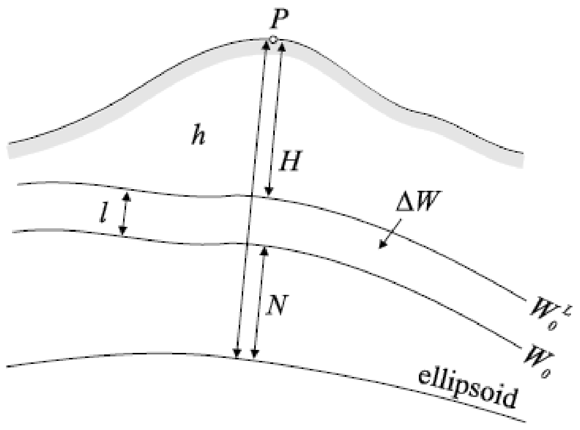


Fig.3 The principle of dermination of vertical datum(Adam Łyszkowicz, Joanna Kuczyńska-Siehień, Monika Biryło,2014)

Determination of geopotential value (W_0^{LVD}) for local vertical datum comes down to estimation of potential difference $\Delta W = W_0 - W_0^{LVD}$ ….(1)

between the potential W_0 of the global vertical datum and the potential W_0^{LVD} of the local vertical datum.

Fig. 3 shows that the geometric quantity l corresponds to the potential difference ΔW can be computed from

$l \approx h - H - N$ ….(2)

for orthometric height (e.g. height above geoid).

The orthometric heights are estimated through the following relationship (Fig. 1)

$H = H_{CD} - Z_0^{absloute} + SST$ ….(3)

Where H_{CD} is the height above the local Chart Datum, $Z_0^{absloute}$ is the absolute mean water level at a tide gauge station and SST is the sea surface topography in the vicinity of the tide gauge station.

It is known from gravity potential theory that ΔW, l and gravity acceleration g or normal gravity γ are related as

$\Delta W \approx l \,.\, g \approx l \,.\, \gamma$ ….(4)

A simplification by using γ instead of g assuming that $\Delta g = g - \gamma$ does not exceed 500 mgal gives an error below 1 mm which can be ignored in most geodetic applications. Taking this into account above equation can be written as:

$\frac{1}{\gamma} \Delta W = l$ ….(5)

If the quantities$h$, H and N are obtained from observations the quantity l can also be treated as an "observation" and then the observation equation for any point (i.e. tide gauge bench mark) assumes the form:

$\frac{1}{\gamma_i} \Delta W = l_i + \gamma_i$ ….(6)

For n observations, the unknown parameters ΔW can be determined by least square (LS) adjustment. However, the presence of the systematic affects and spatially correlated errors in height data, the LS estimation from equation (6) yields a biased result due to improper data modelling. Therefore the removal of systematic effects from the height data is a pre-requisite task and can be performed with the estimation of W_0^{LVD} using an extended observation equation.

$$h_i - H_i - N_i = \frac{W_0 - W_0^{LVD}}{\gamma_i} + a_i^T x + \gamma_i \quad ....(7)$$

Where, the additional term absorbs systematic errors through a set of nuisance parameters x and a_i is a vector of known coefficients depending on the spatial position of bench marks.

3.2 Determination of height of bench marks:-

Once the W_0^{LVD} for local vertical datum (i.e. local geoid) is defined, the geopotential differences between the tide gauge bench marks (TGBMs) and the local geoid may be determined using the equation.

$$W_0^{LVD} - W_0^{TGBM} = \bar{g}.\Delta H = C_{TGBM} \quad ....(8)$$

Where ΔH is the height difference between the Bed Plate of Tide Gauge and the Tide gauge Bench Marks, measured above the local geoid (e.g. Indian Geoid) and $\bar{g}$ is the mean of the gravity value observed at Bed Plate of tide gauge and at TGBMs and C is the geopotential number of TGBMs. Also

$$C_A = C_{TGBM} + \bar{g}.\Delta H \quad ....(9)$$

Where C_A is the geopotential number of any adjacent benchmark ΔH is the height difference between TGBM and the adjacent bench mark and $\bar{g}$ is the mean of the gravity value observed at the TGBM and the adjacent bench mark.

Following the above equation, geopotential number of each bench mark was computed and the entire network of levelling lines was adjusted in least square sense to get the adjusted value of geo-potential number of each of the benchmarks.

Theoretically the orthometric height of a point is defined as

$$H_A = \frac{C_A}{\bar{g}} \quad ....(10)$$

Where C_A is the geopotential number and $\bar{g}$ is the mean gravity value along the plumb line between a point ‘A’ on the surface of earth and the geoid. However, in practice it is not possible to observe the gravity value all along the plumb line, therefore, an alternative method which is most commonly used in practice has been given by Helmert and is given as

$$H_A = \frac{C_A}{(g_A + 0.0424\, H_A)} \quad ....(11)$$

Where H_A is the average height of the survey area in kilometers and g_A is the observed gravity value at point 'A'. The heights derived from the above equation are known as Helmert's Orthometric heights.

4. FUTURE PERSPECTIVE OF MODERNIZATION:-

The modern height reference system concept envisages that it should full the following primary requirements:

(i) It should be defined in the Earth´s gravity field;

(ii) It should be consistent, stable and reliable; compatible with GNSS without geoid model fitting;

(iii) It should be consistent with global and regional gravimetric geoid models;

(iv) It should be dynamic in nature, suitable for scientific research and can be integrated into global height datum;

(v) It should be able to satisfy a large number of economic activities and applications (engineering, cartography, survey, mapping, scientific).

The International Association of Geodesy (IAG) has adopted standards, conventions and guidelines for the definition of international height reference system (IHRS). According to these guidelines, we should adopt [Sanchez 2015]: 1) best-estimated value for the potential W_0 of a height reference surface (geoid), 2) parameters, observations, and data related to the mean tidal system/mean crust, 3) heights expressed in geopotential numbers, 4) positions of points in International Terrestrial Reference Frame (ITRF).

However, the main issues to be considered before the modernization of height reference system are the approaches to be adopted in height modernization. We should decide whether the modernization of height reference system should be based on MSL or the geoid. Several countries in North America, Europe and Asia have started to abandon the MSL/levelling height reference system and are adopting a geoid/GNSS based height reference system. The first such implementation has been adopted in New Zealand [Amos & Featherstone 2009]. In 2013, Canada replaced the old vertical datum dated from 1928 (CGVD1928) [Veronneau *et al.*2006]. USA is planning to establish new height reference system by 2022 and is currently investing significant efforts in improving their data [Roman & Weston 2012]. Some other countries have recently discussed this issue, including Australia [Featherstone *et al.* 2012], Turkey [Ince *et al*. 2014] and South Africa [Wonnacott & Merry 2011]

5. CONCLUSION:-

The international experience shows that national and regional height datum definitions have limited life-span and should be replaced or upgraded every few decades. This is also the case with the traditional mean sea level (MSL) height datums that have significant limitations. These limitations could be successfully solved by defining a new height datum that could exploit all advantages of GNSS and precise gravimetric geoid models with addition to promising surveying techniques such as Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), Airborne Laser Scanning (ALS) and Synthetic Aperture Radar (SAR).

Since the definition and the realization of the IVD was performed more than a century ago, immense changes in terms of technology, data and user requirements have occurred. Although even the redefined IVD will still be realized through a sparse leveling /gravity network yet it will help in computation of a precise gravimetric geoid model for India consistent with GNSS. The precise gravimetric geoid of accuracy of the order of 1-2 cm will serve a long-term solution for Indian height reference system. Without significant time and financial investment the redefined IVD does no longer satisfy the demands in terms of cost and time efficiency. Redefinition of the height datum by determination of precise gravimetric geoid model is very promising and cost efficient technique. Its long-term benefits should trigger its implementation. Consequently, strategy development and planning should start as soon as possible.

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BIOGRAPHICAL NOTES:-

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