Dhar, S., Balasubramanian, N., Dikshit, O.,
Schuh, H. (2022): Stable and upgraded
horizontal datum for India. - Current Science,
123, 43-51.

https://doi.org/10.18520/cs/v123/i1/43-51

Stable and upgraded horizontal datum for India

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A precise datum is significant as a starting or reference point for a multitude of activities like floodplain maps, property boundaries, civil surveys, precise agriculture, crustal deformation and climate studies, and works requiring consistent coordinates. A large nation like India, with almost its own tectonic plate, must have a well-defined network of horizontal datum for determining accurate and reliable 3D positioning for every user, anywhere and anytime. This article discusses the significance, methodology of realization and transformation, applications and static/dynamic coordinates for paving the way for a National Horizontal Datum in India.

Keywords: Geodetic survey, horizontal datum, reference frame, tectonic plate, three-dimensional positioning.

A set of geometrical or numerical quantities, or constants which serve as a reference for other quantities, forms a datum[1]. Generally, in geodetic surveying, two types of datum are considered: horizontal datum, which approximates the shape of the Earth for determination of accurate positions, and vertical datum to which elevations are referenced[1,2]. The specific interest of this article, horizontal datum, forms the basis for providing precise geometric positions, i.e. latitude, longitude and ellipsoidal elevation, of any point on the Earth's surface. For this, at least eight constants are needed to form a complete horizontal datum: three to specify the origin of the coordinate system, three to specify the orientation of the coordinate system, and two to specify the dimensions of the reference ellipsoid[3]. Such a theoretical and mathematical definition is known as a reference system and the realization of such a system to make it accessible to the users is known as a reference frame[3]. Datum is synonymous with the reference frame.

To simulate the Earth's surface mathematically, ellipsoids have been considered[3]. There are different ellipsoids based on whether they justify the surface of the whole Earth or specifically just a country[1]. These were realized by tedious triangulation surveys, using traditional equipment like theodolites, set up mostly on hilltops or large towers, as they depended on line-of-sight restrictions. The advent of satellite technology, especially the Global Positioning System (GPS), made the traditional techniques and old datums outmoded. Unlike the traditional approach of a physical survey, this modern technology has considerably eased human effort, and provided wide coverage and highly precise observations for geodetic survey networks. On the other hand, there is a strong global requirement for accurate positioning, navigation and timing as well as machine guidance and control[4]. All these can be fulfiled by Global Navigation Satellite Systems (GNSS) receivers, continuously operated on the survey control points to realize a strong horizontal datum for the region[4]. This forms a CORS (Continuously Operating Reference Stations) network[4]. The adjusted CORS network has the perfect capability to provide well-referenced, accurate and reliable spatial data, and support satellite and other related applications even in real-time. Such coordinates can also be connected to regional, e.g. Asia-Pacific Reference Frame (APREF)[5] and global, e.g. International Terrestrial Reference Frame (ITRF)[6], reference frames for a range of highly accurate global applications.

The National CORS network has rapidly become the most preferred system for accurate 3D positioning worldwide. Many influential nations have a well-maintained, highly accurate, accessible and consistent national horizontal datum[7]. They all have a common mission to provide precise coordinates at any time and anywhere[8]. USA has a National Spatial Reference Frame (NSRF) with CORS as its foundational component[7]. It has approximately 2000 CORS with 20+ years of data, which are run by various government, academic and private organizations[7,9]. This defines the robust National Horizontal Datum of the USA that enables the user to determine geodetic latitude, longitude and elevation at any point within that country and its territories[9]. In Australia, to closely align the national datum to ITRF2014, refinements were made in its old datum, resulting in Geocentric Datum of Australia 2020 (GDA2020)[10]. The coordinates were computed using a rigorous 3D network adjustment of all available GNSS (>6 h) and terrestrial data, and the transformation parameters were derived from CORS[10]. The German Reference Network (DREF91) was developed in April 1991 by a GPS campaign for the first time to replace the Bessel ellipsoid (1841) as the reference surface[11]. The network consists of 109 sites with a maximum standard deviation of 1–2 cm horizontal[11] and is being regularly updated. In 2016, Germany established the integrated geodetic spatial

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*For correspondence. (e-mail: sujata@iitk.ac.in) reference as a holistic approach for spatial reference[12]. The DREF91 (2016) consists of 250 control stations and 350 reference stations of Satellite Positioning Service of the German State Survey (SAPOS)[12], which is the GNSS CORS network of federal states[13]. The realization includes three hierarchically adjusted networks to provide sub-centimetre accuracy[13]. These brief insights will help in assessing the situation in India.

The status of India's horizontal datum has not been considered holistically. This article discusses major steps to initiate a stable and upgraded National Horizontal Datum (NHD) in India. Here stability refers to the ability of the reference frame to maintain its consistency over time[3]. However, this geodetic infrastructure is a shared national asset required to maintain international leadership in economic and scientific committees, support national security[3] and satisfy all other crucial national needs.

Present status of the National Horizontal Datum in India

With the limited resources available to the user community, the following is the known status of NHD in India. Early in the 19th century, the Great Trigonometrical Survey (GTS) was commenced[14] as a basis for mapping the general topography of India[15]. Almost the whole country was covered by traingulation[14]. Due to the limitation of instrumentation techniques at that time, the accuracy achieved was within a few hundred metres[15]. In the past, the Indian geodetic datum was based on the Everest ellipsoid; a locally fit ellipsoid developed in the 1830s from a combination of several triangulation networks[16,17]. This was the least satisfactory of all the major datums[17], as it could not be extended too far from the origin[1]. Also, with the advent of the satellite era, the old geodetic control of India was inadequate for most of the geodetic, geodynamic, geophysical and defence applications[15], as this required global datum. At that time, WGS-84 was widely used by many countries as the datum for mapping[15,18]. Therefore, in 2005, a transformation campaign was conducted to determine the transformation from Everest to WGS-84 (ref. 16). This method was a quick solution to the insufficient Indian datum problem and for acquiring improvized coordinates without much hassle. In this transformation campaign, 300 GTS stations were selected[16] and 72 h of static GPS observations were made to compute their WGS-84 coordinates. Then with the coordinates available in both systems, i.e. WGS-84 and Everest, transformation parameters were calculated and distributed to the user community[16]. These transformation coordinates were accurate up to ~3 m (ref. 16). Therefore, it was decided that the accuracy was good enough for 1 : 50,000 scale maps[16]. As emphasized earlier, this method was not the best to get an improved Indian datum, but a quick fix for carrying out geocentric applications. As the chosen control points were the then-existing GTS stations, their distribution was not uniform for the whole country. Moreover, ITRF had started becoming more recognized than WGS-84 (refs 6, 19). So, to introduce a re-defined version of the Indian geodetic datum, a new realization campaign was brought in by the Survey of India (SoI) in 2005, simultaneously with the transformation campaign. It started with phase I, in which around 300 new GPS (first-order) control sites were established all around India with 200–300 km distance between them. Unlike the GTS stations of the previous campaign, these new chosen benchmarks were uniformly distributed and selected by an extensive reconnaissance survey. The permanent survey monuments were established on these sites using forced centring devices to mark the exact reference point. Static GNSS observations for 72 h were made on these first-order control points and fixed precise coordinates were determined. Three IGS stations (DGAR, KIT3, LHAZ) were considered to fix the independent coordinates of each station in ITRF05. Then, phase-II was planned to densify the geodetic control network with around 2400 stations (second-order control) with 30–40 km distance between them. However, the development of the second phase did not go as planned. Even the already established control network was not updated and maintained over a long period to serve the purpose of proper horizontal datum for India. According to ground reports, many of these survey control monuments were destroyed during the various developmental activities and vandalism due to lack of awareness. The adjusted network was not readjusted to take into account the destroyed and damaged control stations and their data. Hence, the Indian geodetic datum failed to achieve its purpose and precise coordinates were not available for any applications requiring sub-centimetre accuracy. This adversely affected the user community in India and many scientific developments in the country[15]. SoI is trying to combat this situation with infrastructural plans, and this article will certainly assist in the endeavour by highlighting significant steps and providing some beneficial recommendations.

Modern-day realization of the National Horizontal Datum

As a modern-day realization of NHD, CORS should fulfil three significant goals – accessibility (equipment should be fast, inexpensive, reliable and improving), accuracy (resistance to distance-dependent errors and benchmark instability), and consistency (eliminating systematic errors and aligning with the latest global reference frames)[19]. Let us discuss the sequential steps required to realize NHD through the GNSS CORS network in India.

Network procedure

The National Geodetic Network will comprise three hierarchical levels or tiers[4,20], such as the first-, second- and third-order control points. The first-order network will be an ultra-high accuracy CORS network equipped with geodetic quality receivers that can track all broadcasted global/regional navigation satellites, stable antenna monuments and IGS site compliant features[4,20]. These points should be well distributed across the country[2] and its coordinates must support the definition of a global reference frame[4,20]. The second-order nationwide network will densify the latter and will be adjusted under the condition that the three-dimensional coordinates of all the first-order control points are fixed[2]. They will be equipped with similar features as the first-order CORS, but will be normally operated and maintained by national or State Government agencies[4,20]. The third-order CORS points will be equipped with basic interoperable receivers[4], for further densification of the second-order network, within 15–20 km or less point density[13]. The above three network levels are hierarchically adjusted[13]. The final outcome will provide precise geographical coordinates (latitudes and longitudes) and ellipsoidal heights at any point in the country with sub-centimetre accuracy.

Set-up of CORS infrastructure

Here we discuss some key aspects of establishing the CORS infrastructure. The primary instrument will be a continuously observing dual-frequency GNSS receiver, including Indian Regional Navigation Satellite System (IRNSS) signal-receiving capability. The infrastructural guidelines should comply with the IGS standards adapted to suit the Indian conditions[21]. The site conditions should have minimal impact on the measurement[3]. The receivers should operate to guarantee the efficiency of the network and the long-term quality of its products[20,21]. The antennas should be stable and comply with the best multipath reducing measures[21]. Tough security and safety measures should be in place to increase the longevity of the antennas. Lastly, the CORS receivers should cover the whole Indian subcontinent evenly and be densely distributed to serve any user with the best possible accuracy.

GNSS data processing and analysis facilities

Data centres (DCs) should be established with state-of-the-art facilities to receive observational data from the permanent CORS network in India. Good-quality checking routines like Unix/Hatanaka compression/decompression, TEQC quality, etc., should be incorporated to avoid storing poor data[22]. All the stored quality observations should comply with the common guidelines of the data format. The NHD stations will upload receiver-independent exchange (RINEX) data in the DCs[23]. They will be analysed in the analysis centres (ACs). The ACs acquire quality data to generate precise station positions and velocities of datum points[23]. Also, the ACs should provide weekly/daily output for qualitative analysis. Graphical visualization tools, e.g. residual plots, correlation coefficient plots, etc., should be used for quality control of the recorded data[22]. A few local ACs should be set-up to introduce redundancy in the results to eliminate any systematic errors from a single solution. To fulfil this mission, a good combination tools and proper weighing of individual solutions are imperative.

Network adjustment

The quality of a geodetic network depends on the precision[3] and reliability of the coordinates[24]. In an ideal situation with no errors, this step would not be necessary. However, no measurement is free of errors; hence, adjustment is necessary to distribute these errors in the best possible way. The least-squares technique provides a dependable means for determining the best possible coordinates of survey control points and their uncertainties from a redundant set of measurements[25].

According to Lee *et al.*[2], there are essentially two classes of network adjustment for geodetic surveying.

Minimally constrained adjustment: To assess internal observations independent of external control, minimally constrained adjustment is used. In a geodetic network, this adjustment makes the coordinates of only one station fixed, i.e. cannot be adjusted in position and orientation. In this way, no errors, except those due to the current observations, will be accounted for in the network. This will provide internal precision of the derived coordinates in the survey and allow to check for outlier existence and remove them. It is also used to validate measurements and readjust a-priori weights.

Overly constrained adjustment: After removing of the outliers in the previous adjustment, fully or overly constrained adjustment is performed. This is carried out by fixing at least three stations in order to define the datum, orientation and scale of the network. Therefore, all GNSS–CORS of the network are held fixed. Likewise, for adjusting the second-order network for precise coordinates, an over-constrained adjustment is carried out with the first-order control points held fixed. This adjustment should be tested to verify that the imposed constraints do not result in measurement failure[25].

After the network is adjusted, a statistical measure of how well the adjustment results match the expected outcome of the observations is carried out. This is given by the a-posteriori variance factor. Once the adjusted results pass the a posteriori test, the reference network of NHD is suitable for use.

Maintenance and upgradation of the network

The rigorous realization of the datum based on CORS network requires constant monitoring of the coordinates and

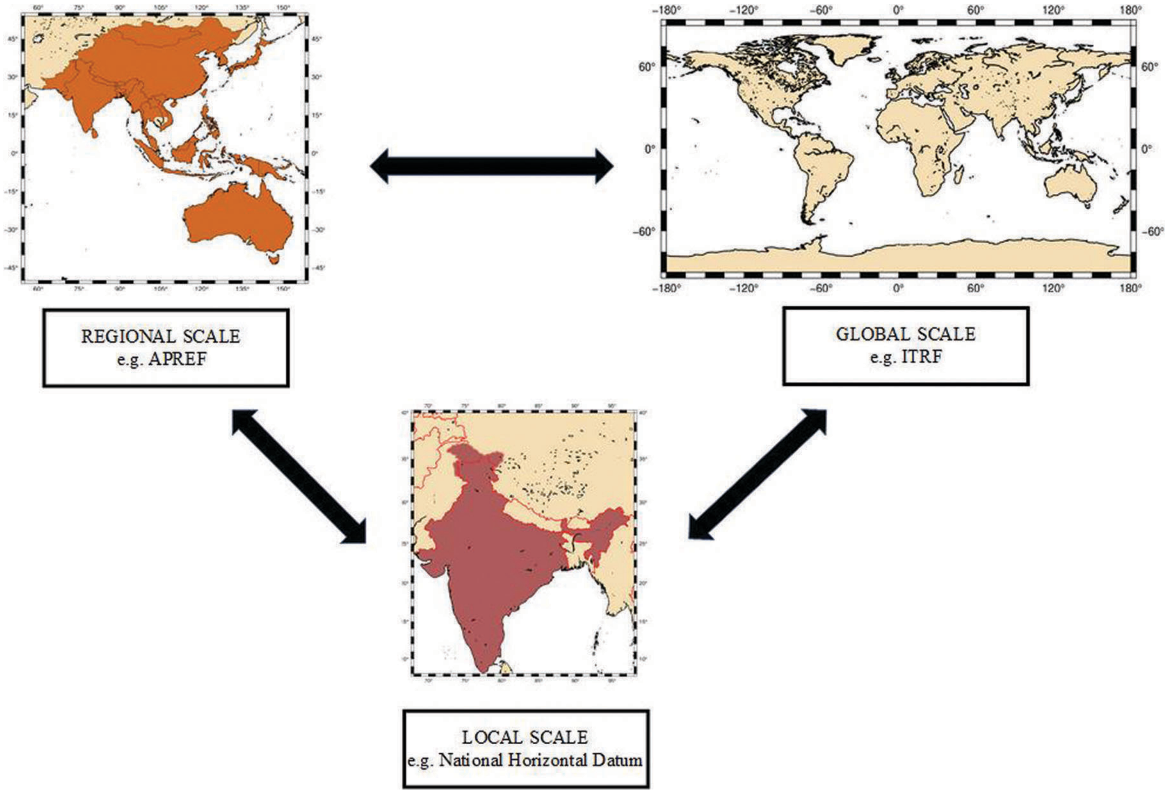

Figure 1. Transformation levels between different terrestrial reference frames.

velocities of the stations defining the datum. These defining stations must be maintained over the years. Each station on the ground is important for realizing the datum, and even the smallest change in any of the stations will cause a change in the adjusted network of the datum and have subsequent effects in providing precise coordinates to the users[3].

Upgradation of the network is important from time to time to bring in improved methodologies for better functioning and quality of the products. The periodic upgrades are necessary to take care of the following.

(i) Expanding to every nook and corner of the country by installing new stations in the area gaps of the previous network[7].
(ii) Modernizing with technological advancements.
(iii) Ensuring higher accuracy of the datum.
(iv) To be in sync with the improved and modified global standards, e.g. latest ITRF realization.
(v) Incorporating all the dynamic changes of the Indian Plate in the periodic updates.

Transformation to global/regional reference frames

It is necessary to determine transformation parameters from the local reference frames to those of global and regional frames in order to study global and regional phenomena respectively[26,27]. Then, the observations from the same geodetic stations can be used for local, regional as well as global applications, as required. The most commonly used methodology is to convert coordinates from one system to another, deploying a least-squares principle and known fundamental points, whose coordinates are known on both systems[16,28]. Therefore, more common control points in NHD with those of regional and global systems are required for good transformation[27]. India has five IGS registered stations (IISC, HYDE, LCK3, LCK4, JDPR) which are a part of ITRF realization and one APREF registered station (IITK)[29]. A country like Japan, which is about ten times smaller than India, has 14 IGS stations[29] and ten APREF stations[5]. This indicates that India should consider investing in modern geodetic infrastructure at the same pace as other countries. Figure 1 depicts the level of transformation with respect to NHD.

International Terrestrial Reference System (ITRS) is a global spatial reference system co-rotating with the Earth in its diurnal motion in space[4,6]. It is geocentric and time-dependent[6,27], i.e. its coordinates change with a linear function of time due to tectonic motion[28]. It is realized by four space geodetic techniques[6] – Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and GNSS[3,4]. Therefore, adopting other techniques in India along with CORS will help align NHD more closely with ITRF. The regional frame, APREF, is realized from the integration of the well-sampled velocity fields of the Asia and Pacific regions from regional and national permanent GNSS networks[5]. Suppose here we consider Indian Reference Frame (INREF) as our NHD, we can see the transformation approach between ITRF and INREF. On similar lines, the transformation of INREF to APREF or any other terrestrial reference frame will be considered.

The 3D similarity transformation connects two frames with different geodetic datums of different origins, orientation around three axes and scale[6,11]. This leads to the basic equation of the seven-parameter (one scale, three translations and three rotations) Helmert transformation as[6,28]

$$X_2 = X_1 + T + D \cdot R \cdot X_1, \tag{1}$$

where D is the scale factor.

The cartesian coordinates are in X matrix.

The subscripts 2 and 1 denote the two frames, with 2 being the desired output and 1 being the input or the start frame.

$$X_1 = \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}, X_2 = \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix}. \tag{2}$$

T is the translation vector of the origin along the X, Y, Z axes.

$$T = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}. \tag{3}$$

R is the rotation matrix around the X, Y, Z axes, with angles α, β, γ (counter-clockwise in RHS) respectively. So,

$$R = R_z(\gamma) \cdot R_y(\beta) \cdot R_x(\alpha). \tag{4}$$

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix}$$

$$R_y(\beta) = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix}. \tag{5}$$

$$R_z(\gamma) = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Therefore, the general model of transformation from one reference frame to another will be[27,30]

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} + \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}_{1,2} + \begin{bmatrix} D_{1,2} & -R_{z(1,2)} & R_{y(1,2)} \\ R_{z(1,2)} & D_{1,2} & -R_{x(1,2)} \\ -R_{y(1,2)} & R_{x(1,2)} & D_{1,2} \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}. \tag{6}$$

Now, specifically discussing the transformation approach from ITRF*kk* (e.g. ITRF14) to INREF*nn* (e.g. INREF21)[27], both are in different epochs, i.e. *kk* and *nn*. Input data will be the ITRF*kk* and INREF*nn* station coordinates and the velocities of common GNSS control stations at the reference epoch, t_r. However, the transformations will be computed at the campaign epoch, t_c. For ease of writing the equations, X^I and X^IN denote the cartesian coordinate matrix in ITRF and INREF respectively. The dot above X in the equations (7) and (8) below denotes their velocities.

According to Boucher and Altamimi[30], the following transformation approach can be applied[30]:

(i) The ITRF coordinates of the common control stations in recent ITRF*kk* will be transformed from t_r to t_c using eq. (7).

$$X^\mathrm{I}_{kk}(t_\mathrm{c}) = X^\mathrm{I}_{kk}(t_\mathrm{r}) + \dot{X}^\mathrm{I}_{kk} \cdot (t_\mathrm{c} - t_\mathrm{r}). \tag{7}$$

(ii) Now, ITRF*kk* at t_c will be transformed to ITRF*nn* using the latest IERS published values of seven transformation parameters, using eq. (6).

(iii) Then, eq. (8) will be used to transform from ITRF*nn* to INREF*nn*.

$$X^\mathrm{IN}(t_\mathrm{c}) = X^\mathrm{I}_{nn}(t_\mathrm{c}) + T_{nn} + \dot{R}_{nn} \cdot X^{I}_{nn}(t_\mathrm{c}) \cdot (t_\mathrm{c} - nn). \tag{8}$$

The above three-step procedure can be performed in one step using 14-parameter transformation between ITRF*kk* and INREF*nn* (refs 27, 31). The transformation has to be flawless for high-precision applications. Therefore, assessing the accuracy and reliability of the resultant transformation parameters is important. This can be done on some chosen checkpoints as an independent check by comparing actual and transformed positions[28]. The transformation parameters have to be standard, readily available and easily accessible to avoid any confusion among the user community.

Static and dynamic coordinates

Static and dynamic coordinates have their own significance with respect to different applications. Traditionally, the static reference system was used with fixed benchmarks on the ground as control[32]. The coordinates of such control points are fixed at the reference epoch and are time-independent[32–34]. Such unaltered coordinates are

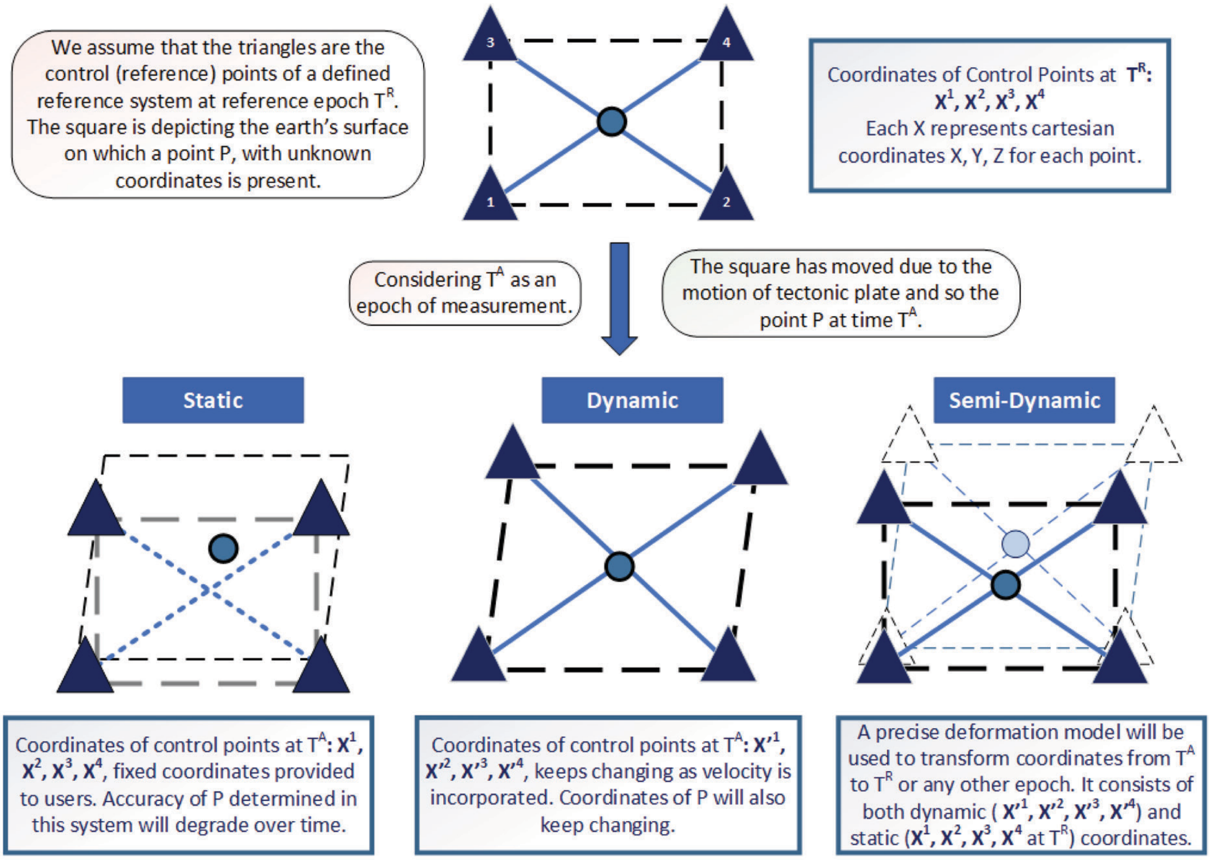

Figure 2. Representation of three types of geodetic terrestrial reference frames.

useful for administrative purposes like mapping, cadastre, and practical applications that can ignore tectonic motion[34]. In reality, the Earth's surface is continuously moving due to plate tectonics[26] and local deformation events like earthquakes, landslides, etc.[32,33]. This results in the deterioration of the static coordinates over time. A major disparity occurs due to the fact that the GNSS orbits are calculated with respect to ITRF[6]. Thus, the GNSS conferred positions will deviate drastically from those of the static coordinates. Over time, when the degraded accuracy of the static coordinates falls below the GNSS accuracy and user expectations, it is time for renewal[32,33]. Upgrading the static reference frame is laborious and expensive[32], and hence cannot be done frequently. To fulfil the sub-centimetre accuracy needs of real-time applications and to study the Earth system, time-dependent coordinates are necessary. This is provided by the dynamic reference system[27], which is based on the global ITRS coordinates[32,34]. This system is complex and confusing for many users, as the coordinates are continuously changing with no proper epoch[33,34]. This renders it unsuitable for many practical applications[32,33]. For exploiting the advantages of these two geodetic reference systems, the semi-dynamic (semi-kinematic) reference system is widely used[32,35]. This is based on the CORS control network, which provides time-dependent coordinates and determines the national deformation model incorporating local movements[33,34]. The semi-dynamic system uses this deformation model to transform dynamic coordinates consistently to a fixed reference epoch[32,33,35]. It provides quasi-static coordinates with reference to a specific epoch, which does not vary until they exceed a certain critical level[34] so that non-geodetics can avoid the complexities of the dynamics. Figure 2 gives a pictorial representation of the concept discussed here. Countries like New Zealand and Australia, where horizontal plate motions are up to 5–7 cm/yr follow the semi-dynamic reference system[8,10,35]. Therefore, this approach is highly recommended for a tectonically active country like India, which is subjected to plate movements up to 5–6 cm/yr and other intra-plate activities[34,36]. This will avoid the expenses updating the static datum regularly without compromising of the accuracy of the coordinates[32,33].

Benefits

The burning question nowadays is 'Where on Earth am I?' From a pilot to a geodesist, this question is of utmost importance and accordingly requires different precision in positions[3]. Therefore, the range of accuracy of the required coordinates varies from metres to millimetres.

The multifarious activities of huge economic, social and environmental impacts now depend directly or indirectly on the precise positioning data[19,37,38]. The following are some highlights from the wide range of NHD applications.

Societal applications

1. It will provide a precise reference for surveying that is significant for many engineering works like construction of roads, rails, canals, pipelines, powerlines, communication infrastructures, etc.[4,39].

2. The global reference coordinates are not modified to accommodate changes from local deformations. At that time, NHD is updated for the changed positions and gives actual coordinates in the affected nation. For example, 'Japan and Chile could not use the ITRF after the 2010 earthquakes'[39].

3. It will assist in providing disaster relief efforts in emergency healthcare and delivering of basic needs like food, water or clothes to the exact locations of disaster-hit areas in the country[4,19]. Such inaccessible locations can be reached by air ambulances, drones or helicopters.

4. It will help manage land resources by improving the cadastral mapping[39] and providing 'definitive' national and various administrative boundaries[41].

5. With the growing purchasing power, smartphones account for almost 80% of the global installed base of satellite positioning devices[38] and most applications (apps) use location data for their services[7]. NHD will improve localized positioning data to impart better niche services.

6. More automated vehicles, Unmanned Aerial Vehicles (UAVs), drones and augmented reality platforms are the futuristic goals of society[38]. These will depend solely on reliable and precise positioning services.

7. It can be used to implement the railway network across India with sub-centimetre positional accuracy[41] and can also offer enhanced safety at a lower cost (i.e. railway signalling)[38].

Economic applications

1. Though India's new geospatial policy has democratized mapping, accurate maps can only be developed from good metrological reference, provided by stable static coordinates of NHD[42].

2. It will help map waterbodies around India and become the primary source of PNT (position, navigation, timing) information in them[37,38]. This will certainly be useful for fishermen, recreational boats, freight ships and addressing any distress call.

3. This service will enable precise agriculture by providing good positional accuracy to drones or pesticide-spraying UAVs[38]. It will be vital to the economy as 'agriculture and related industries account for 17% of India's GDP and feeds almost 50% of its workforce'[40].

4. The dynamic coordinates of NHD can be used for Indian satellite orbit determination by tracking localized changes in the control and monitoring stations[8].

5. The aviation market will rely completely on such precise positioning services for the operation and safety of the increasing number of domestic aircraft[38].

6. This service will improve remote sensing by accurate positioning of aerial mapping aircraft[9,19]. It improves the reliability of photogrammetric restitution of large areas, specifically remote and inaccessible terrain[9].

7. The above concept can also be used to assist technologies like LIDAR, InSAR, sonar, etc. in mapping terrains with digital cameras[9].

Environmental applications

1. The variation of vertical crustal velocities at the NHD CORS sites near tide-gauge stations will be used to relate local sea-level changes to global ITRF[9]. This will be beneficial for monitoring ~7500 km of the Indian coastline.

2. It will assist in geodynamical studies by monitoring local deformations and intra/inter Indian plate movements, which are mostly precursors of seismic activity, volcanic eruptions and local subsidence[39].

3. With the analysis of data from ground-based CORS receivers, tropospheric parameters can be obtained as a part of the estimation[9,41], which will support meteorological research in the country and improve weather forecast[3].

4. Local ionospheric models can be developed to mitigate local ionospheric effects using well-suited correction models in space-based geodetic observations[9].

5. Specifically, this will help improve predictions of natural disasters like tsunamis, cyclones, earthquakes, flooding, etc.[7]. Moreover, it will help examine their size and intensity, impact area, and development of early warning systems[3,4] and GIS-based evacuation routes for minimizing crowding and panic.

Conclusion

NHD forms the pillar of georeferencing in India and its applications have been emphasized here (Figure 3). The concept of NHD is not new to India, and there have been past realizations of the Indian datum. However, science in this respect has taken a big leap globally, but India's progress in this sector is substandard. We have dependent more on the global reference frame than our local frame for indigenous applications. Establishing a well-defined network alone for better NHD is not sufficient. The defining network station coordinates must be adjusted and maintained diligently, transformation parameters have to be determined and repetitive epochal campaigns should be conducted for exceptional updates. Shortcomings

Figure 3. Applications of the Indian CORS infrastructure of the National Horizontal Datum.

in any of these integrated processes will affect the precise positioning services, vital defence and scientific studies in India. Moreover, an accuracy of ~2 cm in the GNSS-derived heights of the CORS network will help in developing better vertical control for the whole country[1,4,10,19].

From the geodynamic point of view, India is in a unique position with its own tectonic plate. So, it becomes much more important to have our own spatial reference frame to monitor the changes in coordinates locally. Moreover, it can be geographically and temporally interpolated or extrapolated whenever and wherever required within the Indian subcontinent, according to local needs. Though most of the key points have already been discussed above, the following are some crucial points from the user's perspective for a better NHD.

- It should be consistent in all parts of the Indian subcontinent[7].
- The static coordinates must not change frequently[32].
- The dynamic coordinates should be closely aligned with the global system so that we can have better coordinates for many global applications like airport obstacles, freight ships, etc.
- Accessible transformation tools with contemporary programming and consistent transformation parameters must be provided[7,19].
- There must be an increase in the number of common points in global, regional and national reference frames, i.e. IGS/ITRF, APREF and NHD respectively, across the country to get good transformation[28].
- Co-location with other existing space geodetic infrastructure, i.e. VLBI, SLR and DORIS of India, is essential to strengthening the link between the national frame and ITRF[7,19].
- A formal publication of NHD is required, which can be accessed by the users and the scientific community.
- There must be awareness among the people about the significance of these geodetic monuments of NHD and stricter laws must be implemented to protect them. This initiative will preserve these structures from destruction and vandalism.
- A competent body with a large workforce should be chosen to establish and monitor the status of the control monuments and replace/repair their instrumentation in case of failure.
- Another proficient body should help coordinate the NHD network, and act as a coordinator between station operators, DCs and ACs, and maintain the product and information system[23].
- India should develop its own software for quality checks, processing of CORS data and monitoring the geodynamic activities of the Indian Plate exclusively.
- The necessary periodic campaigns must be conducted for NHD upgradation and incorporation of changes.
- Regular training and tutorials must be provided to the user community.

The above points reveal that an integrated approach from various competent organizations is predominant for the proper functioning of the NHD service. With this, we can aspire for a better future for NHD in India.

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Received 24 September 2021; revised accepted 10 April 2022

doi: 10.18520/cs/v123/i1/43-51