**Report**

*of*

**Brainstorming session**

**on**

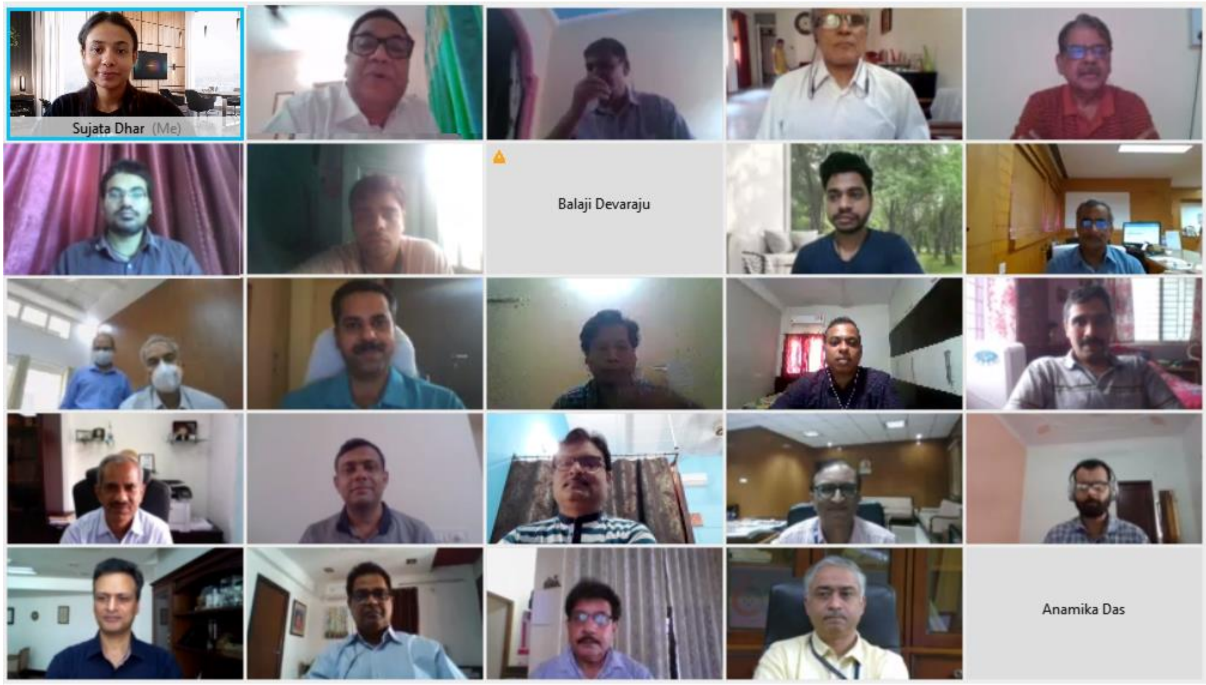
# Indian National Geodetic Infrastructure: Current status and a way forward

**(May 6-7, 2021)**

*Organized by*

## National Centre for Geodesy

**Indian Institute of Technology Kanpur**




**Group photograph of participants of the brainstorming session**

From top (left to right):

**Row-1:** Ms. Sujata Dhar, Prof. Onkar Dikshit, Dr. A.K. Singh, Dr. P. S. Acharya, Maj. Gen. Prof. B. Nagarajan.

**Row-2:** Dr. Ashutosh Tiwari, Mr. Arnab Laha, Dr. Balaji Devaraju, Mr. Digivijay Singh, Dr. G. A. Ramdas.

**Row-3:** Dr. U. N. Mishra, __________, Dr. Jagat Dwipendra Ray, ______, ________,

**Row-4:** Dr. M. Ravichandran, _______, Prof. Dheeraj Kumar, Dr. Raj Kumar, Mr. Ropesh Goyal.

**Row-5:** Dr. T. Srinivasa Rao, Mr. Subhash Kumar, Dr. S. K. Singh, Dr. V. M. Tiwari, Dr. Anamika Das.

## TABLE OF CONTENTS

# Brainstorming session on Indian National Geodetic Infrastructure: Current status and a way forward

**6-7 May 2021 (online mode)**

## 1. Background

It is unanimously agreeable that the new Guidelines for acquiring and producing Spatial Data Services including Maps, issued vide DST F.No.SM/25/02/2020 (Part-1) dated 15th February 2021 are very thoughtful and proactive and will definitely boost the functioning of Geospatial Industries in India. Moreover, it is also self-convincing that the availability of comprehensive, highly accurate, granular, and constantly updated Geospatial Data will significantly benefit diverse sectors of economy.

However, following are a few observations regarding the new guidelines issued on geospatial data collection and also for the upcoming detailed Geospatial Policy:

a) Geospatial Data collection and preparation of maps follow the survey principle of 'whole to part'. Few decades back, the horizontal coordinates of a point on the surface of the Earth were usually referred to Great Trigonometric Survey (GTS) station coordinates and the heights to the Indian Mean Sea level (IMSL) Datum.

b) With the introduction of space-based technologies and modern Survey techniques, the required accuracy of point positions and contour heights have increased several folds. In this scenario, to refer the horizontal and vertical position of a point on the surface of the earth, we do not have precisely defined Horizontal and Vertical Datum in the country, as per today's requirement.

c) We have the levelling lines run all through the country twice, which in itself is a challenging task. We had IVD1905 and RIVD2009, but both have defined with the then best available data and strategy, as thought by one organisation. The IndGeoid versions alpha and beta, National Geoid models, are also established but none of them has been actually computed for the whole of country. Moreover, there are limitations of the developed models due to non-availability of the precise and dense gravity data. Despite various organisations working in this regard, a common discussion has never been conducted.

d) We have a well-distributed set of GNSS observed ground control points (GCPs). However, they have never been adjusted as a whole network and as such we do not have a horizontal datum as well. Moreover, there is an ambiguity in the use of WGS84 and GRS80 reference ellipsoids, and WGS84 and ITRF reference frames. Please note that none of them is either a national datum or an adjusted geodetic coordinate system. Also, if we would like to dwell in with the international standards, we further might have to consider permanent tide system (tide-free, zero-tide or mean-tide systems) to have a consistent data. The setting up of numerous Continuously Operating Reference Stations (CORS) can be utilised to define the static/dynamic horizontal datum for India.

e) Gravity data has been collected in India for over more than a century that was started using a brass pendulum. There have been joint efforts of several premier Indian organisations to prepare a gravity map for India, known as Gravity Map Series of India. However, different organisations used instruments with varying least count and accuracy. Moreover, geophysicists are more interested in Bouguer anomalies carrying out the gravity reductions with any arbitrary height (most used by them is the precise ellipsoidal height) while geodesists are more interested in free-air anomaly or the Bouguer anomaly computed using precise orthometric height. Hence, there is no standard operating procedures followed to make the data collection consistent. Moreover, we never had a well-defined, consistent and precise national gravity datum. It is only Indian National Gravity Datum 1963 or the IGSN71, that has ever been established in India. Also, as per new guidelines, it has been mentioned that gravity data up to 1 mgal can be supplied to any indenter, but it has not been mentioned, if it is the raw gravity data or Bouguer or Free-air anomaly data.

f) We have a well distributed tidal network. Survey of India also maintains the tide gauge stations at many international ports. However, a consistent analysis of them has never been carried out. Coasts are the most important but notorious regions. Hence, mapping high-resolution geodetic/oceanographic sea surface topography at the coast is very important for several projects which have never been carried out for India. Tidal data is also important to define local geopotential value. The present local geopotential value also can cause north-south tilt in the datum because it has been constrained at eight tide-gauges.

In summary, the new geospatial policy has tremendous scope for the progress of the geospatial sector in all domains including industry, research, and academia. The most welcoming step in the guidelines are thoughts towards maintaining the consistency and avoiding the duplication of the geospatial data in the country.

However, these two aspects can only be met only if we have precisely defined geodetic infrastructure, i.e., Horizontal, Vertical, Gravity and Tidal datums. Currently, there are no *standard operating procedures* also for the collection of the various geodetic/geospatial data.

Most of the countries have either developed their geodetic infrastructure and now refining/updating the same or in the process of establishing their geodetic datums (e.g., NSRS in the USA, NGRS in Australia, NGRF in Russia and ECRS in Europe). The establishment of the four datums for the country is the need of the hour, which we have collectively termed as INGReF. Despite the importance in scientific and industrial applications of each datum, individually, they all are interlinked. The need of the geodetic infrastructure has always been acknowledged in the country but never been discussed among all the stakeholders.

From India, we have Dr. V.M. Tiwari, NGRI as a member of IAG-JWG 2.1.1 on Establishment of the International Gravity Reference Frame, Dr. S.K. Singh, SoI (retd.) is the member of IAG-SC 1.3e on Asia-Pacific Reference Frame and Mr. Ropesh Goyal, IITK is the member of IAG-SC 2.4e on Gravity and Geoid in the Asia Pacific. Despite participation of the Indian nationals in the international efforts of developing precise regional/global geodetic infrastructure, the same has never been discussed at our national level.

### 1.1 Applications of the National Datum

The burning question nowadays is "Where on Earth am I?" To a sailor in the middle of the ocean or to a pilot in the sky, this question makes sense, and a reliable answer will be within a meter. To the bridge builders or the operators of precise mining or agriculture, an accurate answer will be upto to a few centimetres. For operation of automated vehicles, UAVs or drones, this question is of utmost significance and their whole working depends on the precision of their position. In military applications, having accurate knowledge of target is very important. Though, it's not so obvious for a geodesist, geologist or a climate scientist to ask this question, but you will be surprised to know that they require millimetre accuracy for research and development in their fields.

With the advancement of technology, our need to know where we exactly are on Earth at any given moment has increased. **As a result, innumerable activities of enormous economic, social and environmental values, now depend directly or indirectly on the global and local precise positioning data.** Importantly, the National datum can be geographically and temporally inter -/ extrapolated, whenever and wherever required within the Indian subcontinent, as per needs.

Any geodetic service or applications require precise datum as starting or reference points for multitude of activities like, floodplain maps, property boundaries, construction surveys, levee design, or other work requiring accurate coordinates that are consistent with one another. Precise Datum is very important for determining accurate and reliable positioning for everyone. The **Horizontal datum will provide geocentric, three-dimensional positions with sub-cm accuracy, in a unique homogenous reference system for the whole India, while the vertical datum does the same for height.** Therefore, the National Datum infrastructure and this updated technology is crucial for wide range of applications and its imperative need is explained in the following part.

**(a) Societal**

1. This will help in Precise point positioning which are required in many works like cadastre, engineering (tubes, power lines), precise navigation, etc.
2. The global coordinates are not modified to accommodate changes in local coordinates after local calamities, they are required to relocate the positions and give actual station coordinates of the affected Nation. For e.g. Japan and Chile could not use the ITRF after the 2010 earthquakes.
3. This technology will help to provide efficient emergency healthcare facilities to remote areas within the Nation.
4. This will also help to provide relief efforts, monitor and get updates from disaster hit areas during any such event, when global coordinate services will be ineffective.
5. With the growing purchasing power, smartphones account for almost 80% of the global installed base of satellite positioning devices and which require accurate reference system for majority of the applications (apps) for its services. A local reference system will help to provide specialised localized services to its consumers.

**(b) Economic**

1. Though new Geospatial policy has democratised mapping. But accurate and precise maps remain the backbone in many increasingly sophisticated applications.
2. The CORS network will help to maintain the timing which are core of many critical infrastructures, including telecoms, energy, finance and driving future shipments.
3. It can used to compile a multipurpose dataset which is meant to be the "definitive" description of the national boundaries.
4. It can be used for implementation of railway network across India with superior 1-2 cm positional accuracy and also, offer enhanced safety for lower cost (i.e. railway signalling).
5. This will support the Autonomous driving by providing reliable and accurate positioning.

6. It will also help to map the sea and will become the primary means of obtaining PNT information at sea.
7. This service will represent a key enabler for the integrated farm management concept. The positioning in drone will help as its uptake in agriculture is increasing, accounting for over half of the commercial market.
8. The time-dependent coordinates from the National Datum can be used for satellite orbit determination and tracking changes in local station coordinates, due to local seasonal and periodical effects.
9. This service will also help remote sensing. The accurate positioning of aircrafts employed in aerial mapping is crucial to improve the reliability of photogrammetric restitution primarily for large-scale aerial survey applications over remote and inaccessible terrain.
10. The above concept can also implement for geolocating landmarks from the air with digital cameras that can be extended to a broad array of mapping terrain applications using cutting edge technologies such as scanning radar, light detection and ranging (LIDAR), inertial systems, interferometric synthetic aperture radar, and/or sonar.

**(c) Environmental**

1. Geodynamics and global change studies are based on time-dependent station coordinates; hence it will help to identify mm-level local deformations (uplift/subsidence) which are indications for seismic precursors and effects of climate change (sea-level rise), within the Nation.
2. With the routine analysis of a network of ground-based CORS receivers, tropospheric parameters will be obtained from a part of estimation, which will support the climate research of the country.
3. Crustal motion applications are one of the most obvious of all applications and will give information about intra-plate movements within the country.
4. The variations of vertical crustal velocities at CORS sites near tide gauge stations may be used to determine the "absolute" sea level changes with respect to ITRF. This type of analysis was impossible to conduct before the proliferation of CORS in coastal areas.
5. Wide area ionospheric models can be developed to model and mitigate local ionospheric effects.
6. The CORS data along the 7,500 kms coastline of India will help relate the local sea level changes.
7. Specially, this will help to improve predictions of tsunami size and impact area to provide early warning information used to optimise evacuation routes, minimise crowding and panic.

In the light of above points, one and a half day brainstorming session on the 'Indian National Geodetic Infrastructure: Current status and a way forward' was conducted in an online mode. This brainstorming session was a common platform for the Government, industry, academia, research institutes, army, DRDO and the competent surveying agency of the country to discuss the current status of the national geodetic infrastructure and a way forward to the INGReF.

This brainstorming session was conducted among a set of key people/organisations who all can contribute based on their expertise and experience toward arriving at recommendations, policy documents, guidelines, roadmap, handholding, supporting infrastructure, etc., thereby construct a joint fundamental team for the development of the INGReF.

This meeting is the first step towards a very ambitious but indispensable goal for development of the INGReF.

**2. Conduct of the brainstorming session**

Initially, it was planned to hold an offline meeting for the brainstorming session on "Indian National Geodetic Infrastructure: current status and a way forward" at the IIT Kanpur Outreach Centre, NOIDA during 6-7 May 2021. This arrangement was necessitated as we anticipated intensive discussions and decisions from the session to decide the scope and framework of the INGReF.

Though offline discussions are irreplaceable but noting the escalating situation of second wave of Covid19 in various parts of the country, it was decided to hold the session in an "online mode." This ensured the safety of all participants without affecting their valuable participation in the deliberations of the meeting.

The meeting was conducted for two days, i.e., 6-7 May 2021 using WebEx platform. The meeting had following four major sessions:

a) May 6, 2021 (0915-1015): Prof. Onkar Dikshit, Coordinator, National Centre for Geodesy, welcomed all the participants and provided an overview of the overall conduct of the brainstorming session. Prof. B. Nagarajan, Chairperson, National Geodesy Programme, delivered a talk to introduce the concept of INGReF to all the participants. This was followed by a talk on DST's view on INGReF and its importance by Shri. P. S. Acharaya, Head, National Geospatial Programme, Department of Science and Technology.

b) May 6, 2021 (1020-1330): Invited presentations of ~15 minutes each were given by the following organizations: Survey of India, National Geophysical Research Institute, Defence Research and Development Organisation, National Centre for Polar and Ocean Research, National Institute of Ocean Technology, National Remote Sensing Centre, Space Application Centre and Indian National Centre for Ocean Information Services. Military Survey (MO-GSGS) also shared their views on the overall INGReF concept. Finally, the session was concluded by Prof. Balaji Devaraju, Assistant Professor, IIT Kanpur who summarized all the presentations.

c) May 6, 2021 (1430-1700): In order to realize the goals of the meeting in an efficient manner, four themes were outlined for discussion and theme members were also identified according to the expertise and interest of the participants. Four breakout rooms were created, in WebEx, pertaining to each theme, i.e., a) horizontal datum, b) vertical datum, c) gravity datum, and d) tidal datum. The participants joined their respective breakout rooms for group discussion and formulating the group recommendations.

d) May 7, 2021 (1000-1400): One member from each group presented their group recommendations for the feedback/comments from all the participants. Prof. Onkar Dikshit (IITK), Dr. S.K. Singh (SoI, Retd.), Prof. B. Nagarajan (IITK), and Prof. Balaji Devaraju (IITK) presented the group recommendations for horizontal datum, vertical datum, gravity datum and tidal datum, respectively.

The meeting ended with vote of thanks by Prof. B. Nagarajan.

## List of participants

| Horizontal datum group | Vertical datum group |
|---|---|
| Dr. Onkar Dikshit, IIT Kanpur, Convener | Dr. S. K. Singh, SoI (Retd.), Convener |
| Dr. Ashok Kumar Singh, DST | Prof. Dheeraj Kumar, IIT-ISM |
| Dr. Nitin Joshi, Survey of India | Mr. Varun Kumar, SoI |
| Dr. Kaushik R. V., ISRO | Dr. A. P. Singh, NGRI, |
| Dr. D. Ram Rajak, ISRO | Dr. Ganesh, ISRO |
| Dr. John Mathew, ISRO | Dr. Manish Saxena, ISRO |
| Dr. Nishkam Jain, ISRO | Mr. A. Kartik, ISRO |
| Dr. Ruban Jacob, Geospatial Infrastructure | Dr. I. M. Bahuguna, ISRO |
| Dr. Jagat Dwipendra Ray, IIT Kanpur | Dr. Ritesh Agrawal, ISRO |
| Ms Sujata Dhar, IIT kanpur | Dr. Ashutosh Tiwari, IITK |
| | Mr. Jai Prakash, IIT Kanpur |
| | Mr. Ropesh Goyal, IIT Kanpur |
| **Gravity datum group** | **Tidal datum group** |
| Maj Gen (Dr) B. Nagarajan, IIT Kanpur, Convener | Dr. Balaji Devaraju, IIT Kanpur and Convener<br>Dr. Rashmi Sharma, ISRO |
| Dr. U. N. Mishra, Survey of India | Dr. Sharad Chander, ISRO |
| Col. Arjun Sampath, MO-GSGS | Dr. Sreejith, Scientist, ISRO |
| Dr. Ashish Shukla, ISRO | Dr. Vamsi, Scientist, SAC ISRO |
| Dr. Nirmala, ISRO | Dr. R S Mahendra, INCOIS |
| Shri G. Kannan, RCI | Dr. Sudheer Joseph, INCOIS |
| Dr M. Sree Ramana, RCI | Dr. Sunanda, Scientist, INCOIS |
| Shri Murali Krishna, RCI | Shri Subash Kumar, Trimble |
| Ms. Drishti Agarwal, IIT Kanpur | Digvijay Singh, IIT Kanpur |
| Mr. Arnab Laha, IIT Kanpur | |

### 3. Horizontal datum group

As per Vanicek and Wells (1974) "A coordinate system in three dimensions is a set of rules that describes each geometrical point in the three-dimensional space by a corresponding ordered triplet of numbers, called *coordinates*. The geometrical object generated by fixing the values of two of these three numbers is a coordinate line. The geometrical object generated by fixing the value of one of these three numbers is a *coordinate surface*. A *datum* is a specific coordinate surface. A set of rules associating each coordinate triplet in one coordinate system with a new triplet is a *coordinate transformation*. If these rules are expressed as an equation, it is the *transformation equation*. If a transformation equation involves numbers other than the old and new coordinate triplets, those numbers are the *transformation parameters*.

Thus, a horizontal datum involves a set of constants specifying the coordinate system used for geodetic control i.e., for calculating coordinates and elevations of points on Earth. It forms the basis of computation of horizontal positions on the Earth. Geographic data represent the locations and attributes of things on the Earth's surface. Locations are measured and encoded in terms of geographic coordinates (i.e., latitude and longitude) or plane coordinates (e.g., UTM). To measure and specify coordinates accurately, one first must define the geometry of the surface itself. The horizontal datum can be accessed and used through a collection of specific points on the Earth whose latitude and longitude have been accurately determined.

Thus, a national horizontal datum is a specified coordinate system for a collection of positions on the surface of the earth to provide geocentric, three-dimensional positions with desired accuracy, in a unique homogeneous reference system for the whole nation.

Traditionally, horizontal datums have used classical surveying methods (i.e., measuring distances and angles through triangulation surveys) to best fit to the surface of the earth. However, with the availability of a variety of geodetic sensors such as GNSS, SLR, DORIS, VLBI, etc. we now have access to high precision horizontal datums, satisfying international, regional, and national requirements.

#### 3.1 International Status

The material for this section has been liberally taken from the cited references given under the list of references for horizontal datum (Appendix-II).

One of the main tasks of modern geodesy is to define and maintain a *global terrestrial reference frame*. The quality of the reference frame realization has important implications for our ability to study both regional and global properties of the Earth, including post-glacial rebound, sea level change, plate tectonics, regional subsidence and loading, plate boundary deformation, and Earth orientation excitation, dynamics of mass transport within the Earth system, etc. (Bosy, 2014).

In July 2003, the *International Association of Geodesy* (IAG) established the *Global Geodetic Observing System* (GGOS: http://www.ggos.org) to integrate the three basic components: *geometry*, *the earth rotation* and *gravity* with the help of existing global ground network, based on the geodetic space techniques: *very long baseline interferometry, satellite laser ranging, global navigation satellite systems and Doppler orbitography and radio positioning integrated by satellite*. The *global reference frame* in the GGOS is a realization of the *International Terrestrial Reference System* (ITRS). The ITRS is a world spatial reference system co-rotating with the Earth in its diurnal motion in the space. Figure 1 shows 5 levels of the GGOS infrastructure, which depend on the distance to the Earth' surface.

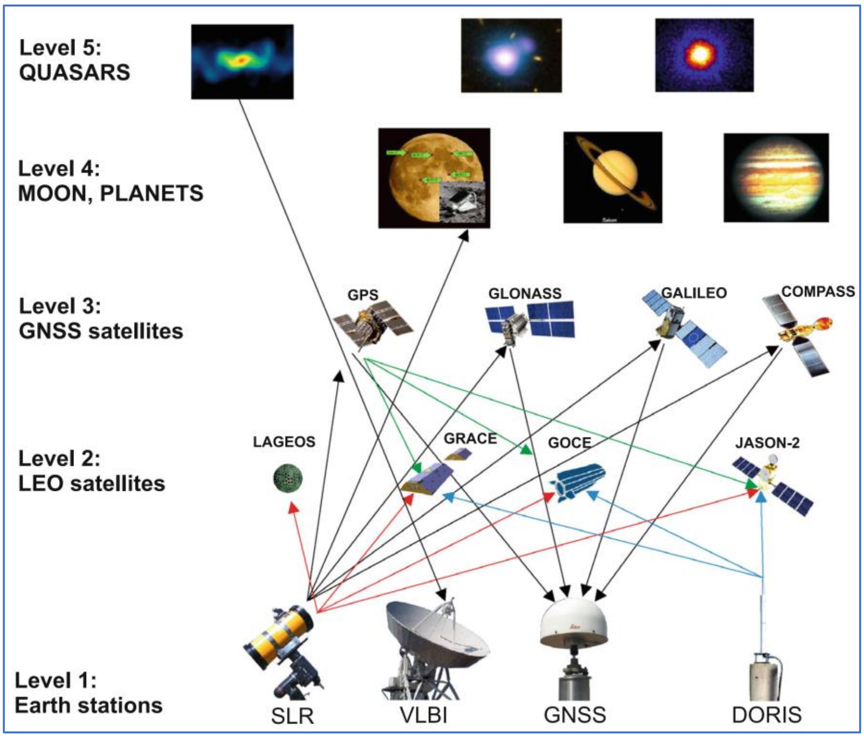



Figure 1: GGOS: An observing system of layered geodetic infrastructure (Gross et al., 2009)

The *International Celestial Reference System* (ICRS) forms the basis for describing *celestial coordinates*, and the *International Terrestrial Reference System* (ITRS) is the foundation for the definition of *terrestrial coordinates* to the highest possible accuracy. The definitions of these systems include the orientation and origin of their axes, scale, physical constants, and models used in their realization, e.g., the size, shape and orientation of the reference ellipsoid that approximates the geoid and the Earth's gravity field model. The coordinate transformation between the ICRS and ITRS is described by a sequence of rotations that account for variations in the orientation of the Earth's rotation axis and its rotational speed (Blick *et al.*, 2014).

While a *reference system* is a mathematical abstraction, its practical realization through geodetic observations is known as a *reference frame*. The conventional realization of the ITRS is the *International Terrestrial Reference Frame* (ITRF), which is a set of coordinates and linear velocities of well-defined fundamental ground stations. In the case of the ITRF these are the observatory stations of the IGS, ILRS, IVS, IDS ground networks, derived from space-geodetic observations collected at these points, and computed and disseminated by the International Earth Rotation and Reference Systems Service (IERS).

There have been several different realizations of the ITRF since 1989, each designated as ITRFyyyy where yyyy refers to the year of observation for the most recent data used in the computation of station coordinates and velocities. This may be different to the reference epoch, which is the date to which station coordinates and velocities are referenced. Initially computed on an annual basis, since 1997 the new ITRF realizations have been released by the IERS at 3–5 year intervals with each successive ITRF more internally accurate than the previous one accounting for difference in the coordinates of the ground stations between different epochs on account of motion of stations due to local crustal deformation and global plate tectonics.

International Association of Geodesy (IAG) has a number of sub-commissions responsible for the definition, realisation, and maintenance of *regional reference frames*. Regional reference frames are *densified*. That is, they include a larger number of GNSS CORS from the region, while also including the CORS used in the global reference frame determination that maintains a strong connection between the global and regional frames. Examples of regional reference frames include the *European Reference Frame* (EUREF), the *African Reference Frame* (AFREF), *System Reference for Central America and South America* (SIRGAS) and the *Asia-Pacific Reference Frame* (APREF). Various guidelines/specifications have evolved for using CORS in defining the frames. For example, the CORS site under consideration for APREF must be in operation for more than two years before being considered for inclusion. Two years is considered the minimum length of time required to compute a statistically significant coordinate and site velocity. As with ITRF, regional reference frames are defined by the coordinates and site velocities of contributing stations. The key difference with some regional reference frames (e.g., EUREF and NAD83) and ITRF is that the site velocities may be with respect to the dominant tectonic plate encompassed by the frame and not a no net rotation (NNR) condition. This approach minimizes site velocities. Regional frames not constrained by the motion of a single tectonic plate are closely aligned with ITRF.

Unlike ITRF, which is built on observations from SLR, VLBI, DORIS, GNSS/GPS, the *national terrestrial frames* are connected to ITRF through a network of GNSS stations. Typically, a national geodetic infrastructure is built using GNSS continuously operating reference stations (CORS), enabling modern, more accurate and less costly national reference frame which are easy to maintain than achieved via old classical approaches and provide easy access to the ITRF to give inter-operability of geospatial data between countries. These also enhance various scientific studies, national development, capacity building & international cooperation in Geodesy for knowledge transfer know how.

The following paragraphs briefly describe various initiatives in other countries in establishing the national reference frames.

**(1) USA**

In USA, the *National Oceanic and Atmospheric Administration's* (NOAA's) *National Geodetic Survey* (NGS) is responsible to *define*, *maintain*, and *provide access* to the USA *National Spatial Reference System* (NSRS), for meeting its economic, social, and environmental needs. The NSRS constitutes the official system of the civilian government for enabling a user to determine geodetic latitude, longitude, and height, plus orthometric height, geopotential, acceleration of gravity, and deflection of the vertical at any point within the United States and its territories. The NSRS contains information about its orientation and scale relative to international reference frames, as well as the precise orbits of all satellites used in defining or accessing the NSRS. The NSRS also contains all necessary information to describe *how all of these quantities change over time*.

Initially, with a desire to establish a high accuracy reference network (HARN), also called a high precision geodetic network, many new reference marks were located in more accessible places (e.g., near public roads and/or to provide a relatively less obstructed view of the sky).

As a forerunner of to the CORS network, the *Cooperative International GPS Network* (CIGNET) was conceived in 1987. Each CIGNET site was equipped with a high quality dual frequency GPS receiver that continuously recorded signals from GPS satellites. The primary intention was to make dependable tracking data available from a network of ground stations to compute precise ephemerides (orbits) for the GPS satellites. Soon, the concept of covering the entire United States with a network of CORS to enhance the NSRS was conceived. Around this same time, several other federal agencies were also starting to establish networks of continuously operating GPS base stations, but for different reasons:

- *US Coast Guard (USCG):* to supplement its LORAN radionavigation service by offering the differential GPS (DGPS) service to support safe marine navigation in USA coastal waters.
- *USA Army Corps of Engineers (USACE)*: for a cost efficient navigation system to support their inland waterway operations (dredging), hydrographic surveys, etc. They collaborated with the USCG to extend the DGPS service inland along several of the major rivers.
- *Federal Aviation Administration (FAA):* to use some type of CORS to support safe air navigation. They also developed Wide Area Augmentation System (WAAS).
- *NASA's Jet Propulsion Laboratory (JPL)* and *USA Geological Survey (USGS):* to use CORS sites to determine satellite orbits and study crustal motion.

Because of the similarities between these projects, **the US General Accounting Office (GAO) directed these agencies to work together and to coordinate activities and equipment procurements to reduce the expense to the federal government and the US taxpayer**. NGS took an advisory role helping to define the GPS equipment specifications needed to support the missions of all these agencies.

In 2008, the CORS network contained stations in the United States, Canada, Mexico, Central and South America, the Caribbean, and Iraq. More than 200 organizations are participating in the program. Figure 2 shows status of CORS network operated by different agencies/organization in USA as on May 2008. Although the number of CORS sites is growing at a rate of ~ 15 sites per month, the total number of permanent GPS tracking stations in the United States is probably growing perhaps twice as fast. Figure 3 shows the current status of CORS network. There is also an ongoing project to determine an accurate orthometric height for each CORS site. Determining the orthometric height of a CORS site may require special methodology depending on the location and the type of antenna mounting. With the current rate of growth CORS network, it is expected to result in an average inter-site distances on the order of 70-100 km in USA.

NGS derived the original realization of the North American Datum of 1983 (NAD83) in 1986 by performing a rigorous adjustment of most of the classical geodetic observations in its archives together with *Doppler* observations and a few *very long baseline interferometry* (VLBI) baselines. This original realization is called NAD83. With improvements in knowledge of terrestrial reference frames, NGS has introduced several newer realizations of NAD83, refining at each step the adopted coordinates. In 1998, NGS introduced NAD83 (CORS96), which is based on the CORS network by defining a transformation from the International Terrestrial Reference Frame of 1996 (ITRF96) to NAD83. In both reference systems, ITRF and NAD83 (CORS96), the 3D positional coordinates of each CORS are complemented by a 3D velocity to account for crustal motion. Similarly, newer realization of ITRF, coordinates and velocities may be transformed to corresponding NAD83 (CORS96) values using available equations and parameters. One needs to apply the adopted velocities to compute positional coordinates for any other epoch date. The coordinates and velocities of the CORS sites form the foundation of the NSRS and the recently completed NAD83 (NSRS2007) readjustment. Further updates of the same, though delayed at present, are also planned.

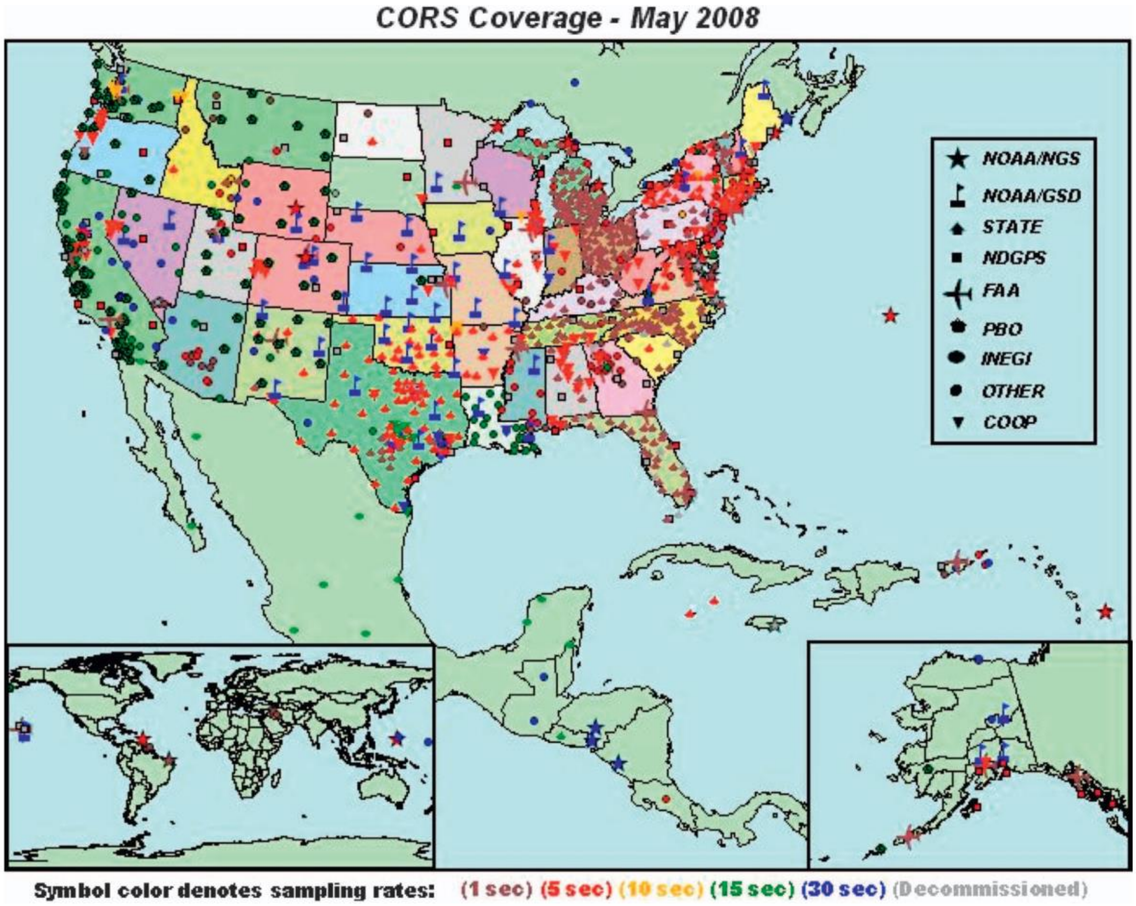



Figure 2: Operational CORS sites as of May 2008, (Snay and Soler, 2008)

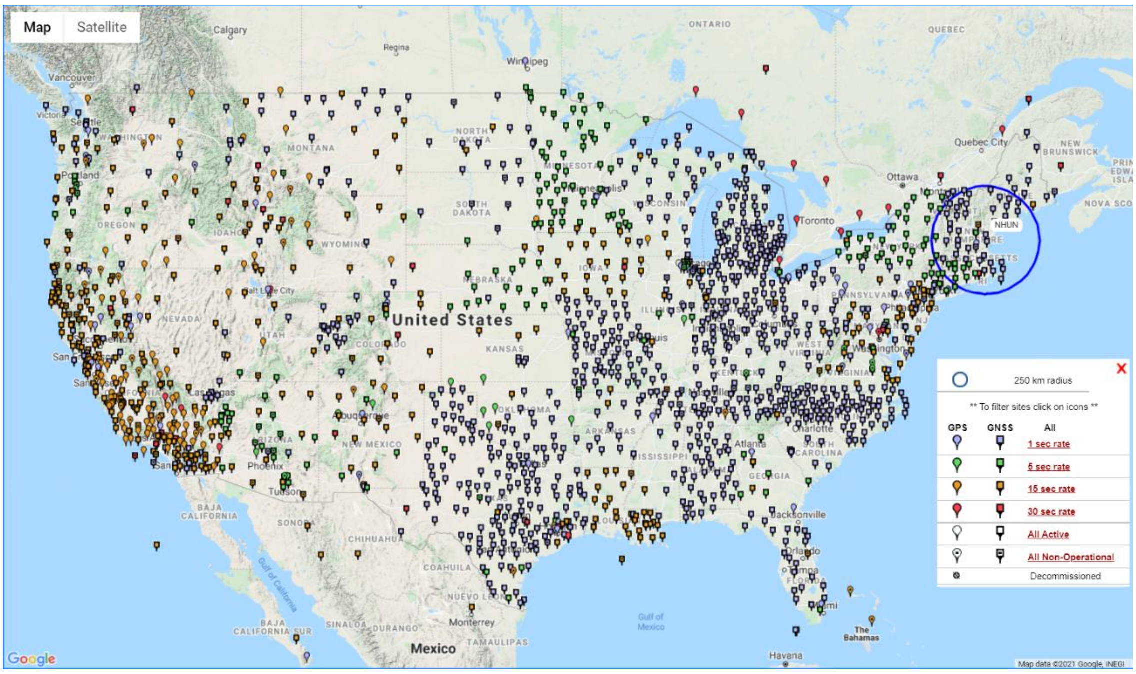



Figure 3: Operational CORS sites as of May 2016, (National Geodetic Survey, 2016).

**Salient features of the system**

**Validation process**

1) With every new CORS site, NGS first uses at least ten 24-h GPS data sets to compute this station's ITRF positional coordinates relative to other stations in the global IGS network.

2) NGS uses the horizontal time-dependent positioning (HTDP) software to predict the station's ITRF velocity.

3) NGS then transforms the ITRF positional coordinates and velocity for this CORS site into their corresponding NAD83 (CORS96) values via the adopted 14-parameter similarity transformation.

4) Every few years, NGS reprocesses all CORS data collected since 1994 to compute provisional positions and velocities for all CORS relative to the current ITRF realization: call it ITRFxxxx. If, for any station, these provisional ITRFxxxx positional coordinates differ from the currently adopted ITRFxxxx positional coordinates by more than 1 cm in the north-south or east-west component or by more than 2 cm in the vertical component, then NGS adopts the provisional position and velocity to supersede the previously adopted ITRFxxxx position and velocity.

**Additional checks**

1) In addition to this validation process, NGS performs a solution for each day to monitor the quality of adopted CORS positional coordinates. Each solution includes all CORS data collected during the 24-h period spanning that day.

2) As a by-product, NGS compiles plots showing differences between the published ITRF coordinates and the values obtained from the daily solutions, corrected for crustal motion, for the latest 60 days. The results are plotted relative to a local horizon (north-east-up) coordinate frame and are made available to the general public through the CORS Web page (ftp://www.ngs.noaa.gov/cors/Plots/ xxxx.pdf); where xxxx denotes the site's four-character identification.

3) The movement or replacement of the antenna or an unexpected natural phenomenon may displace the position of the CORS reference point. Geophysical processes (earthquakes), volcanic activity, etc. may also produce significant station displacements that should be documented.

4) When the trend of the 60-day series of daily estimates differs from this station's adopted positional coordinates by more than the tolerances described in the preceding paragraph (1 cm horizontal; 2 cm vertical), then NGS carefully analyses the available data to determine whether or not this station's published positional coordinates and velocities should be updated.

5) Similar analysis is done with respect to the adopted NAD 83 (CORS96) coordinates. When the daily provisional transformed coordinates referred to the NAD 83 frame differ by more than 2 cm in the north-south or east-west component or by more than 4 cm in the vertical component, then NGS adopts the provisional NAD83 positional coordinates and velocity to supersede the previously adopted NAD 83 values. As a result of these less stringent tolerances, adopted NAD 83 (CORS96) positional coordinates and velocities are less likely to be updated than their ITRF counterparts. However, this NGS policy is being discussed at NGS for possible revision to lower tolerances in response to both internal and external requests.

For those agencies, whose sites are included in the CORS network, NGS computes highly accurate 3D positional coordinates and velocities in the NSRS for their site antennas, provides an international data distribution mechanism, monitors the positions of the antennas on a daily basis, and notifies the agencies when movements of the antennas are detected. In exchange, the agencies notify NGS when they change equipment or software so that NGS can keep CORS users abreast of the status of the CORS sites. Scientific users who monitor very small movements of the Earth's crust are especially interested in any antenna changes so that they can account for those effects when they undertake long-term analyses of site locations. When antenna changes are detected and corrections made, NGS immediately publicizes this information through the CORS Newsletter (http:// www.ngs.noaa.gov/CORS/newsletter1/).

In March 2001, NSRS also provided release of the *On-line Positioning User Service* (OPUS) utility for GPS data. OPUS is an automatic service that requires the user to input only a minimal amount of information; its instructions are self-explanatory, and its Web page contains enough details to be followed easily (https://geodesy.noaa.gov/OPUS/about.jsp; https://geodesy.noaa.gov/OPUS/index.jsp).

**Applications**

In addition to the primary application of CORS, to enable accurate positioning relative to the NSRS, NOAA CORS network (NCN) has been pivotal in advancing other, well documented, multidisciplinary investigations. The scientific literature is flooded with articles citing CORS as the basis for their experiments and/or research projects. The realm of applications is diverse and multifaceted, and it is expected that this trend will continue in the future. CORS has already made an impact on solid Earth science and is on the fringe of significantly impacting atmospheric science. Some applications include upgrading the NSRS, assessing gps observational accuracies, multipath studies, crustal motion, sea level changes, tropospheric studies, ionospheric studies, geolocation of aerial moving platforms, etc. Gradually all CORS receivers are being upgraded to receives data from a different GNSS.

Additionally, several CORS are streaming GPS data in real time to NGS headquarters which will broadcast these data to the public in real time to support the growth of regional GNSS networks that enable real-time positioning in the USA. Several organizations, both public and private, are now establishing such regional GNSS networks. Also, many more of these regional real-time positioning networks are expected to be established in the near future. NGS needs to support these networks by developing appropriate standards and guidelines so that:

a) Promulgated positional coordinates and velocities for the corresponding GNSS base stations are compatible with the NSRS;
b) User equipment can operate with services from different real-time GNSS networks to the greatest extent possible; and
c) Stations contained in each real-time network meet prescribed criteria in terms of stability and data quality.

Accordingly, NGS is considering the possibility of streaming GNSS data from about 200 federally funded CORS so that this agency may understand the intricacies involved in operating a real-time GNSS network to the extent necessary to develop appropriate standards and guidelines. NGS also encourages the institutions, who are providing real-time positioning services, to use the NGS-provided data in their operations so as to (1) supplement the data from other GNSS base stations, and (2) use the positional coordinates and velocities of the GNSS stations contained in the NGS real-time network as fiducial values for determining positional coordinates and velocities of other real-time GNSS stations. NGS also streams these data (GNSS observables and not "correctors" to these observables), which are not streamed by another organization, because USA citizens should have real-time access to data from federally funded stations in the CORS network whenever it is economically and technically feasible to do so.

**(2)** ***Australian Geospatial Reference System (AGRS, [https://www.icsm.gov.au/upgrades-australian-geospatial-reference-system](https://www.icsm.gov.au/upgrades-australian-geospatial-reference-system))***

The Australian Government has committed $225m to provide 10 cm (or better) accurate positioning to anyone, anytime, anywhere in Australia in the near future. This is a significant improvement from the 5-10 m accuracy one can currently achieve using GPS enabled devices. Consequently, an upgrade of a number of elements of Australia's Geospatial Reference System including the introduction of a time dependent reference frame called the Australian Terrestrial Reference Frame are underway.

***(a) Geocentric Datum of Australia 2020 (GDA2020)***

- The Geocentric Datum of Australia 2020 (GDA2020) is a *static* datum – just like GDA94 and has been available for use since 17 October 2017.
- A *static* datum means that the positions of features (e.g., roads, buildings and property boundaries), do not change over time despite ongoing changes in the Earth's surface, e.g., tectonic motion.
- GDA2020 spatial data is more closely aligned to modern Global Navigation Satellite Systems (GNSS, e.g., GPS), allowing users to more easily benefit from modern positioning technology.
- Beneficial for many long-duration applications where it is easier if the coordinates of features do not change (e.g., a major road development project).
- Australia has moved ~1.8 meters north-east since GDA94 was defined in the year 1994. GDA94 to GDA2020 differences will range in size depending on location: ~1.5 to 1.8m due solely to tectonic plate motion and ~1.3 to 2.3m when including regional GDA94 definitions and distortions.

***(b) Australian Terrestrial Reference Frame 2014 (ATRF2014)***

Australian Terrestrial reference Frame (ATRF) enables accurate, reliable, and authoritative time dependent coordinates and a dense velocity field to be derived for all Australian sites. This includes CORS that have been operating for less than two years, passive survey marks such as short term geodetic project control stations and geophysical monitoring of campaign sites.

- The Australian Terrestrial Reference Frame 2014 (ATRF2014) is a *time dependent reference frame* and has been available for use since 1 January 2020.
- A *time-dependent reference frame* (also called *dynamic datum*, or *earth-fixed reference frame*) is used to describe features whose coordinates change with time, e.g., due to plate tectonic motion.
- ATRF2014 coordinates for a feature will change with time as the Australian tectonic plate moves.
- Coordinates expressed in ATRF2014 require a time-stamp in order to be unambiguous.

- A user can choose to use either GDA2020 or ATRF2014 depending on their requirements.
- ATRF2014 is expected to be predominantly used for Intelligent Transport Services (e.g., autonomous vehicles), Location Based Services (e.g. mobile applications), or by the scientific community
- Users can propagate ATRF2014 coordinates through time using the Australian Plate Motion Model.

A National Adjustment is carried out to compute ATRF2014 and GDA2020 coordinates. The process of undertaking the national adjustment will be:

- The national adjustment will be run monthly.
- The national adjustment will be maintained in GDA2020.
- Constraints for the national adjustment will be from a cumulative APREF solution from ~3 months prior. This allows enough time for any discontinuities in the APREF solution to be identified and resolved. The cumulative APREF solution will be propagated to the epoch of 2020-01-01 using the Australian Plate Motion Model.
- The *National Geodetic Campaign Archive* (NGCA) data (i.e., > 6hr GNSS data) will be subject to ongoing revision and included as baselines.
- The *Jurisdictional Data Archive* (JDA) (i.e., < 6hr GNSS data and terrestrial data) will be subject to ongoing revision and will continue to be quality checked by jurisdictions before supplying it to GA to include in the national adjustment.
- The output of the national adjustment will be new GDA2020 coordinates and uncertainties.
- ATRF2014 coordinates will be derived at any epoch by applying the Australian PMM to the latest GDA2020 coordinates.

**(3)** ***Germany (Habrich, 2007; Bruyninx, 2009; Dostal et al. 2018)***

Surveying is the responsibility of the German states ("Lander"). According to the Integrated Geodetic Spatial Reference 2016, all components of the geodetic spatial reference (3d-position, height, gravity) have been planned, measured/observed and analysed together in a common measurement epoch. Uniform Europe-wide reference systems are today the basis for the geodetic spatial reference, which is the basic infrastructure for all user groups. In Germany, the Working Group of the Surveying Administrations of the Federal Republic of Germany (AdV) decided in 1991 to introduce the European Terrestrial Reference System 1989 (ETRS89) as a uniform, official position reference system for the whole of Germany. Today the ETRS89 is implemented in Germany by SAPOS, the satellite positioning service of the German national surveying, highly precise, homogeneous and comprehensive for all areas of surveying. In 1995 the AdV decided to introduce ETRS89 in connection with UTM mapping (see UTM coordinate system). With this decision, there is an obligation for all land surveying administrations to also transfer the components of the real estate cadastre to the ETRS89 / UTM.

With the implementation of the ETRS89 / DREF91 (implementation 2016), the AdV decided on September 21, 2016, to introduce the Integrated Geodetic Spatial Reference 2016. The components in this include:

- DHHN 2016: new official realization of the German height reference system

- **ETRS 89 /DREF91 (2016):** improved coordinates for the German reference network SA POS
- GCG 2016: new official quasigeoid (German Combined Quasigeoid)
- DHSN 2016: official gravity reference frame

The GNSS campaigns were done in 2008 for the supply of coordinates for the realization of the ETRS89/DREF91 (realization 2016) for the GGP-Framework network and for the valid at that time SAPOS reference network. After 1994 and 2002, this is the third implementation of the ETRS89 in Germany. The official realization was originally based on the coordinates of the points of the German Reference Network 1991 (DREF91). In 2002, coordinates were adjusted using observation data and readjustment. A new GNSS campaign in 2008, linked with height and gravity fixed points as well as geodetic basic network points (GGP framework network), finally led to the implementation in 2016. Coordinate changes made (maximum improvements in network solutions) were nationwide at a maximum of –4.8 and +3.6 mm for the position components and 12.8 mm for the height component (Feldmann Westendorff et al. 2016).

The realization of ETRF/DREF91 (realization 2016) followed the below guidelines for its realization (Figures 4 and 5):

- GNSS campaign 2008
    - 250 control stations (GGP)
    - 350 reference stations (IGS/EPN/SAPOS)
- Adjustments without constraints (orbits IGS2005)
- Transformation into ITRF2005
- Transformation into ETRF2000 (memo 8).
- Systematic differences to the Realization ETRS89/DREF91 (2002).
- Transformation into ETRS89/DREF91 (2016) (3 rotations)
    - Differences in the position minimized (no relevant to real property cadastre)
    - Almost no height changes compared to ETRF2000

On similar lines and with upgraded global realizations, another GNSS campaign is planned for 2020 for improving the coordinates for next realization. There are various working groups for managing the positioning in Germany.

- Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany (AdV).
- Working Group Spatial Reference (AK RB)
- SAPOS - Satellite Positioning Services of the German Land surveying
- National Network around 270 stations

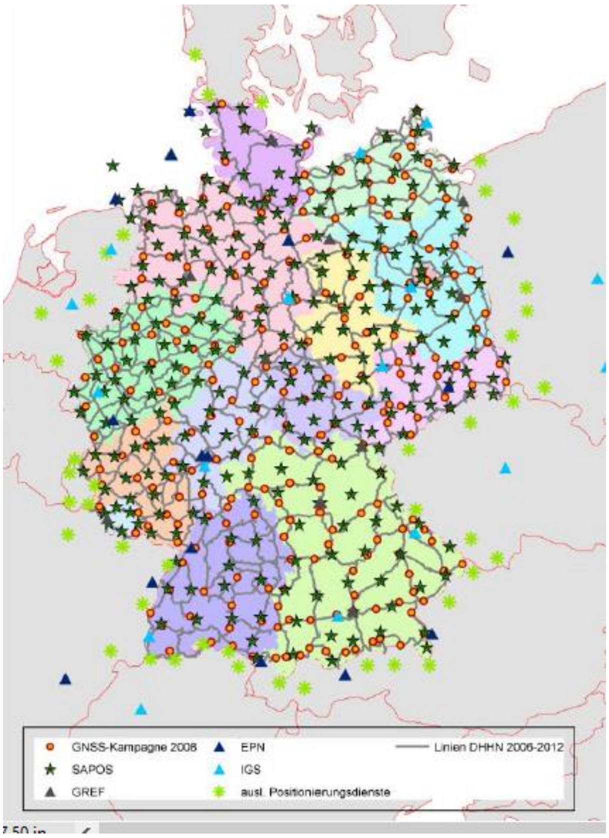



Figure 4: GNSS Campaign 2008

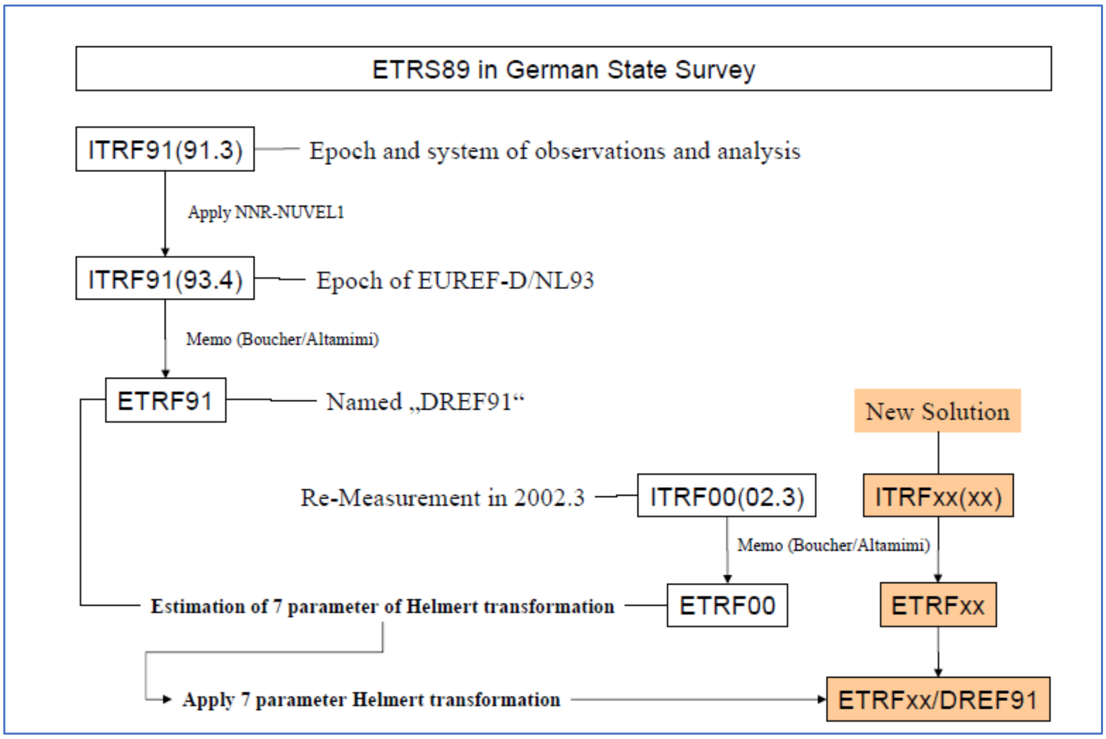



Figure 5: Realization of the New solution of ETRF/DREF91.

**(4)** ***Poland (Bosy, 2014)***

In Poland, the POLish REference Frame (POLREF) was established to provide the EUREF-89 reference frame for geodetic, surveying and mapping applications. The POLREF network initially consisted of 348 points linked to 11 EUREFPOL stations. The average distance between points equals 25–35 km (Figure 6).

In August 2000, the National Spatial Reference System (PSOP) finalized the Polish PSOP which contains definitions and descriptions of the following elements:

- *Geodetic reference system and frame*, called EUREF-89, is an extension of the European reference frame ETRF89 on Polish territory as a result of the diversification campaign EUREF-POL 92, the results of which were approved by the Sub-commission for the European Reference System (EUREF), IAG in 1994.
- *Vertical (height) reference system and frame*, which is composed of gravitational potential values divided by the average values of the normal acceleration of gravity (the normal heights), referenced to the average level of the Baltic Sea in the Gulf of Finland, assigned to a reference point in Kronstadt near St. Petersburg (Russian Federation).
- *Projection coordinate systems (mapping systems)*- flat rectangular coordinate systems 2000 and 1992, which are based on a mathematically unambiguous assignment of the Earth surface points to corresponding points on the plane according to the theory of cartographic Gauss-Kruger projection.

  The ellipsoid GRS80 binds all the components of the Polish PSOP system. The polar coordinates ($B$, $L$ or $\Phi$, $\lambda$) in the geodetic reference system above refers to the GRS80 (WGS84) ellipsoid. For mapping systems, ellipsoid GRS80 projections are used. This greatly facilitates the practical usage of the system and unifies the calculations, such as GIS applications.

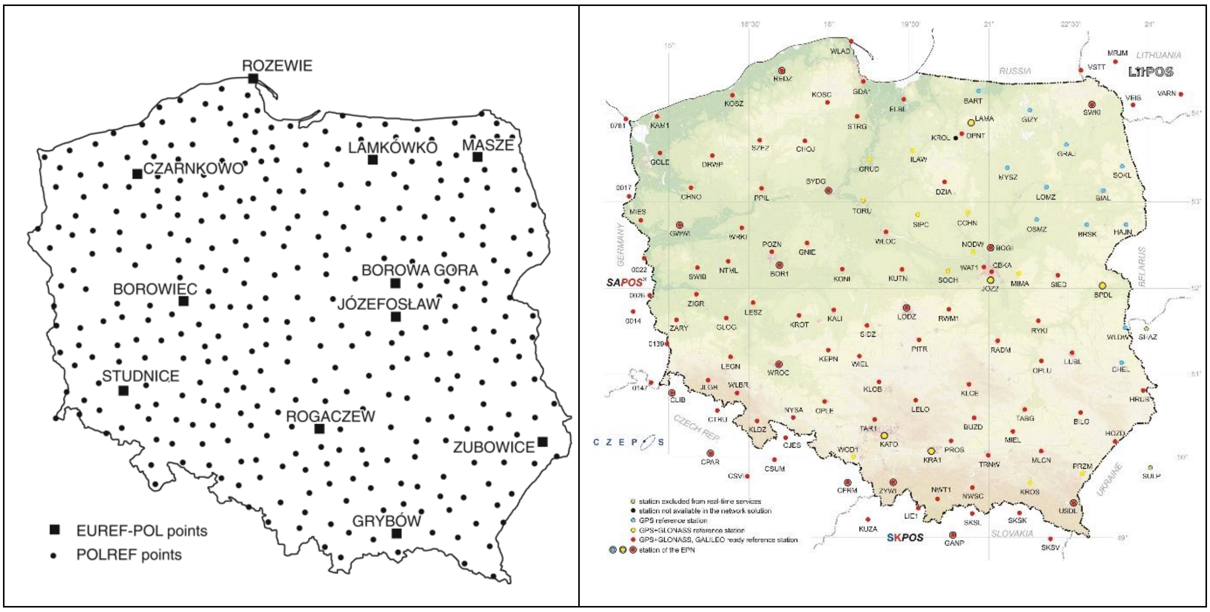



Figure 6 Polish reference frame: (a) EUREF-POL and POLREF network points (b) Distribution of ASG-EUPOS reference stations (Bosy, 2014)

### 3.2 National Status

As part of the National Hydrology Project, the Survey of India is setting up a network of around 200 CORS in Maharashtra, Uttar Pradesh, and Karnataka. However, the primary aim of this set up is to deliver DEM of vertical accuracy of 3-5m & 0.5m for flood modelling, digital Geo-Database of 1:25K scale and creation of Geoid Model of 10 cm accuracy. The CORS is not conceived to evolve to define the horizontal datum for the country. Hence, it appears that currently no effort is underway to define the national horizontal datum.

### 3.3. Suggestions/recommendations

During discussions, Ms. Sujata Dhar, PhD student (IIT Kanpur and GFZ Potsdam, Germany) made a presentation on background of horizontal datum and how it has been realised in a few countries. The Survey of India informed that there is a proposal to set up a CORS Network in the country with 800+ receivers. About 200+ of such receivers have already been operationalized. However, as per current status there is no directed effort in using these CORS for defining the horizontal datum.

The SoI also informed that:

1. These CORS will form Tier-1 reference stations. A few additional CORS receivers will also be set up by a few states.
2. Primary selection criteria for setting up these sites was installation in safe premises with an approximate inter-station distance of 70 km. However, no prior geodetic analysis was carried out to finalize the location for these CORS.
3. Site selection is not based on any simulation studies of design/optimization of the network. Therefore, no results will be available for Network's robustness.
4. These will be based on ITRF2008 coordinates.
5. Current accuracy is 3 m for the transformed coordinates in ITRF2005 from Everest coordinates.
6. CORS network accuracy will be determined only after its complete establishment. The timeline for achieving the same is not available as on date.
7. Policy on data dissemination, quality, charging, etc. still not finalized and is expected to be finalized later by an advisory committee.
8. Not much information is available in the public domain on this effort.

The following members participated in the group meeting on Horizontal datum group:

Dr. Onkar Dikshit

Dr. Ashok Kumar Singh

Dr. Nitin Joshi

Dr. Kaushik R. V

Dr. D. Ram Rajak

Dr. John Mathew

Dr. Nishkam Jain

Dr. Ruban Jacob

Dr. Jagat Dwipendra Ray

Ms Sujata Dhar

A summary of observations made during discussions is given as follows:

**Dr. K. V. Kaushik**

- Interested in incorporating IRNSS data in the geodetic receivers at these sites.
- With the carrier phase measurements, ISRO is planning to improve the positioning accuracies of IRNSS. Hence, it can support the CORS and its applications.
- Keeping in mind the rapid developments on NavIC, ISRO may be invited for possible discussion on integration with the proposed system.

**Dr. Ram Rajak**

- Emphasized on the transformation between field to the global system for GIS/remote sensing applications. There is a need for accurate and reliable transformations.
- Education of the next generation on the reference frames, its adjustments and transformation are very important for the country's future.

**Dr. John Mathew**

- There is a need for (i) a reference frame for static applications like cadastral georeferencing where accuracy requirements are of the order a few centimetres, while (ii) science applications like plate motion studies would require a reference frame that can support accuracy requirements to the order of a few millimetres/year of motion rate, such as the ITRF.

**Dr. A. K. Singh**

- SoI and ISRO should join hands to integrate and have a NavIC ready CORS, keeping in mid the national requirement of having an independent indigenous system and very high cost of the investment.

**Dr. Onkar Dikshit**

- Standards must be finalized and shared with the community including students.
- Two different approaches for setting reference frames, namely Static and dynamic, should be considered.
- For example, in Australia, the Geocentric Datum of Australia (GDA2020) is used as a static datum for positioning of features (e.g., roads, building, property boundaries, major road development projects, etc.). However, a time-dependent/dynamic datum called the Australian Terrestrial Reference Frame 2014 (ATRF2014), and available for use since 1 January 2020, is expected to be predominantly used for Intelligent Transport Services (e.g., autonomous vehicles, Location Based Services (e.g., mobile applications), or by the scientific community.
- SoI informed that the adjustment of the network will be carried out by BERNESE SW. No indigenously developed adjustment SW is going to be used for CORS network

adjustment. This is a long-term project of national importance and efforts should be made for in-house development of geodetic adjustment SW.

- Adjustment of Reference Frame is very important for quality control, and it should be finalized soon by SoI for its CORS Network.

The recommendations from the horizontal datum group are as follows:

1) There should be an integrated and focused effort in defining the national horizontal datum.
2) Upgradation and maintenance of all the CORS Network may be taken up by SoI (the custodian of the network) in collaboration with some other institutions who are familiar with the process.
3) Guidelines for setting up the network based on the current best practices followed by the international community must be evolved and shared with the scientific community. The information on defining this datum should be available to the public for the community involved in various geospatial activities. These guidelines may include, but not limited to (i) distribution of the CORS, inter-station separation (ii) data collection, archival and quality assessment (iii) frequency of network adjustment for re-definition of horizontal datum (iv) designing campaign modes for data collection (v) algorithms to connect the same to the prevailing ITRF (vi) co-location of these stations with other geodetic sensors (viii) evolving standard operating procedures and sharing with concerned personnel (vii) dissemination of the information to the user community.
4) Although presently, there are no plans for densification of the planned CORS Network, it was informed by SoI that many states or organization coming up with regional CORS network, will help to densify the reference CORS Network by SoI. However, to contribute to defining and updating of the national horizontal datum, a highly coordinate and focused efforts must be made, which are presently non-existent.
5) Preliminary studies (simulation) of the CORS Network (distribution/location) are important to have an idea of the expected achievable accuracy of the final network and must be carried out.
6) India should plan to come up with its own Indian Plate Observing Software to maintain and monitor the CORS Network in India.
7) A reasonably accurate and operational datum be made available to the user community very quickly. Further, improvements in the same can evolve with time.
8) Metadata standards should be strictly adhered to for all CORS sites to maintain the data uniformity.
9) Good transformation of the National Reference coordinates to ITRF is required for many applications like plate motion studies, seasonal horizontal deformations, sea level, etc.
10) Significant investment is required in terms of training the new generation of scientists and students on processing and analysis of CORS data and disseminating information for its applications.
11) ISRO, NCG, academic institutions and a few other stakeholders should be involved while discussing the policy on data dissemination, quality, costing, etc.
12) Information on Indian CORS be widely publicized and be made available to user community.

13) Possibility of co-locating CORS with other techniques such SLR/VLBI for future applications.

14) A working group may be set up for definition, realisation, and maintenance of the national horizontal datum.

Following paragraphs briefly summarize some requirements for defining the national horizontal datum.

**3.4. Network Procedure**

The National Geodetic Network can comprise three hierarchical levels, such as the 1st, 2nd and 3rd order control points. The 1st order network will consist of ultra-high accuracy CORS network equipped with geodetic quality receivers that track a good range of satellites, stable antenna monument, IGS site compliant features. These will spread uniformly across the country. The 2nd order nationwide network will densify the latter and will be adjusted under the condition that the three-dimensional coordinates of all the 1st order control points are fixed. The 3rd order control points are CORS networks equipped with "minimum interoperable configuration design" receivers, for further densification of the latter, within 15 – 10 kms or even less point density. The outcome of the three different level networks will be precise geographical coordinates (Latitudes and longitudes) and ellipsoidal heights at any point in the country.

**3.5. Setup of Continuously Operating Reference Station (CORS) Infrastructure**

A key instrument in providing the national horizontal datum will be to cover the Indian subcontinent with continuous observing dual frequency GNSS receivers, including IRNSS receiving capability. These receivers should operate under well-defined standards and guidelines that guarantee the efficiency of the network and the long -term quality of its products.

***(a) GNSS Observation and Baseline Processing***

Data Centres are very important and should be established with state-of-the-art facilities to receive data from the permanent network of GNSS stations around the country. Good checking procedure should be incorporated to avoid the storing of bad data.

Analysis Centres dedicated to such processing and maintaining the datum points should be formed. They should be responsible for providing any related products to the users. Also, these centres should provide weekly output for qualitative analysis and other works. Graphical visualization tools, e.g., the plot of correlation coefficients of the coordinates, should be used for quality control of the recorded data. A good combination tool should be used to combine the weekly solutions. Proper weighting of solutions is imperative for good coordinates.

***(b) Network Adjustment***

There are essentially two classes of network adjustment for geodetic surveying:

*(i) Minimally constrained adjustment*

It assumes that in the case of a GNSS network, only one station is held fixed, i.e., the coordinates of this point are not allowed to move or to be adjusted. This is required to avoid the normal equations becoming singular. For this work, three different levels of the minimally constrained adjustment may be carried out in order to rigorously examine the outlier and modify the stochastic model resulting from the GPS baseline processing. The 'campaign adjustment' and 'integration adjustment', focus on detecting outliers by performing the *Tau* test against standardised residuals resulting from the adjustment. After successful adjustment (i.e., all outliers are removed), an empirical stochastic modelling scheme considers both, internal and external, errors. This processing is likely to be over-optimistic. Therefore, an iterative process is applied for the modelling until the $\chi^2$ (chi-square) test is passed. Therefore, they will indicate the precision of the derived coordinates.

*(ii) Over constrained adjustment*

This is carried out by fixing at least three stations in order to define the datum, orientation, and scale of the network. The adjustment should not be performed until all obvious outliers have been detected and removed or re-measured.

### 3.6. Importance of maintenance of control points and upgradation of network

The network of CORS should be maintained properly over the years, for the coordinates to remain minimally changed and form a strong *consistent datum* for the country. Each point on the ground is important for the realization of the datum and even the smallest change in any of the points will cause the change in the network and will have subsequent effects.

Upgradation of the Network is important to take care of following actions:

- To expand access in the nation and with upgrading technological advancements.
- To ensure higher accuracy of the datum.
- To maintain and be in sync with the global standards/datum so that the network can support various global applications. The solutions should be tied to the latest ITRFyy.
- To incorporate all the dynamic changes of the Indian Plate in the upgraded datum.

## 4. Vertical datum group

### 4.1 International Status

Below we have provided some details on the national vertical datums or national height reference surfaces for the countries that are area-wise larger (except Brazil) than India. The material for this section has been liberally taken from the cited references given under the list of references for vertical datum (Appendix-II).

#### a) Russia (Savinykh and Kaftan, 2019)

The Main Russian Vertical Reference Frame (MRVRF) lines of Russia form a uniform network of level circuits consisting of ~ 170 closed loops of 1st order and about 1000 polygons of class 2nd order and mixed polygons. The perimeters of the 1st order circuits are from 190 km to 2.6 thousand km (an average of 980 km) in the European part of Russia; from 400 km to 4.7 thousand km (an average of 2.2 thousand km) for the Siberia and the Far East. The total length of the MRVRF leveling lines in Russia is 325 000 km, 155 000 km of which is the 1st order, 170 000 km is the 2nd order. The average measurement epoch in the MRVRF of Russia corresponds to 1983, for the 1st order lines - 1989, and for the 2nd order lines of 1977.

#### b) Canada (Amos, 2007; Richards, 2011; NRCan, 2021)

Canada's official vertical datum is called the Canadian Geodetic Vertical Datum 1928. It was established through the adjustment of approximately 124,000 km of precise levelling that was constrained to MSL observed at six tide gauges (spread on both coasts of Canada) in 1928. This adjustment (like NAVD 88) used Helmert orthometric heights.

Until 1993, 4000 km to 5000 km of levelling was carried out by Natural Resources Canada (NRCan), with about 3000 km of this for maintenance purposes. This reduced to 1200 km from 1994 to 2000; from 2001, only minimal targeted levelling has been undertaken (Véronneau et al., 2006). The coverage of the precise levelling data is not uniform, primarily as a result of large areas terrain being unsuitable for this activity and the remoteness of northern Canada. In the case of Canada, the levelling is concentrated along the southern edge of the country.

In 2015, Canada adopted a new height reference system: Canadian Geodetic Vertical Datum of 2013 (CGVD2013). It replaced the Canadian Geodetic Vertical Datum of 1928 (CGVD28). The new system corrects for systematic errors in the old datum and is also realized by a geoid model (CGG2013a) instead of a network of benchmarks whose heights are measured by levelling.

The motivation for this change was simply that levelling was considered unviable for several reasons such as: shortages of skilled staff, increasing costs, dynamic nature of Canadian landmass (GIA effects). Also, the levelling lines had significant distortions (as high as 1.5 m between the coasts), and are not accessible nation-wide (majority of leveling network exists in the South).

#### c) USA (Zilkoski et al., 1992)

The current vertical datum in the United States of America (USA) is the North American Vertical Datum of 1988 (NAVD 88). Its predecessor, the National Geodetic Vertical Datum of 1929 (NGVD 29) is still used in some areas. NAVD 88 incorporated approximately 730,000 km of two-way first and second-order precise levelling in both the USA and Canada, including 81,500 km of re-levelling. The datum was realized by the adjustment of American, Mexican and Canadian levelling data constrained to a single benchmark (Rimouski, Quebec, Canada) located at the mouth of the St Lawrence River. This differed from NGVD 29, which was constrained at 26 coastal tide-gauge sites. NAVD 88 heights are in terms of the Helmert orthometric height system.

Recently, The US National Geodetic Survey (NGS) has resolved to replace the North American Vertical Datum 1988 (NAVD88) with the North American-Pacific Geopotential Datum 2022, i.e., geoid based vertical datum.

However, NGS does accept that levelling still has a role to play in surveying. Once NAPGD2022 is implemented, NGS will recommend that any levelling carried out is controlled by GNSS+geoid derived heights at distances no further than 30 km. This demonstrates that, at the local scale, levelling is still superior and is likely to remain the tool of choice by surveyors for height-critical projects.

**d) China (Hanjiang, 2012)**

The current vertical datum of China is national vertical datum 1985 of which the origin is located in Dagang tidal station, Qingdao. National Administration of Surveying, Mapping and Geoinformation of China (NASG) finished a first order levelling network of 93,000 km including 100 rings in 1984 and a second order levelling network of 136,000km in 1990. The national vertical datum 1985 was built based on these levelling networks. Compared to Yellow Sea height datum 1956, it had some advantages of increased density, improved accuracy and more rational structure. NASG completed re-measurement of the first and second order levelling network from 1991 to 1999, to further improve the accuracy of the national height datum 1985. The height datum in China is a local system, and there is difference up to meters with international height system.

There have been great improvements in the refinement of the geoid model for China. The accuracy of geoid has reached decimetre level nationwide, and it is up to cm-level in some provinces. The goal for near future is to improve the national geoid to cm-level.

The new height datum is proposed to be maintained by the new levelling networks and geoid.

**e) Australia (ICSM, 2021)**

The Australian Height Datum (AHD) is the official national vertical datum for Australia and refers to Australian Height Datum 1971 (AHD71; Australian mainland). The datum surface passes through approximate mean sea level (MSL) realized between 1966 and 1968 at tide gauges around the coastline.

AHD heights were derived across Australia through a least squares adjustment of 97,320 km of 'primary' levelling (used in the original adjustment) and 80,000 km of 'supplementary' levelling (applied in a subsequent adjustment). The interconnected network of level sections and junction points was constrained at the 32 tide gauge sites, which were assigned a value of zero AHD.

The AHD is known to have a number of biases and distortions that are attributable to:

- The ocean’s time-mean dynamic topography (MDT).
- Short tide gauge observation periods.
- The zero reference of the AHD (MSL at 32 tide gauges) is not coincident with an equipotential surface (e.g., the geoid). This largely manifest in a north-south tilt of ~0.7 m in the AHD relative to the geoid across the continent.
- Local and regional distortions due to systematic and gross errors in the Australian National Levelling Network (ANLN) that propagated through the national network adjustments.

Recently, Geoscience Australia has introduced Australian Vertical Working Surface (AVWS). The AVWS is vertical reference for heights, realized by subtracting an Australian Gravimetric Quasigeoid (AGQG) model value from a GDA2020 ellipsoidal heights. The AGQG model provides the height difference between the ellipsoid and the AVWS. It differs from AUSGeoid2020, which provides the offset between the ellipsoid and Australian Height Datum (AHD), by between -1 to 1 m throughout Australia.

The AVWS is not replacing AHD, but instead is an alternative reference for heights for those who wish to use it. A recent user requirements study (Brown et al., 2019a; Brown et al., 2019b) found that AHD is not capable of meeting some user requirements; predominantly when working over distances greater than 10 km. This is predominantly due to localized errors and distortions in the AHD. When deriving AHD heights from GNSS and AUSGeoid, users are able to achieve accuracy of 6-13 cm. The alternative, AGQG, is accurate to 4-8 cm and will improve over time as data is added (predominantly from airborne gravity).

**4.2 National Status**

Indian Vertical Datum (IVD) was defined in 1909 by constraining the MSL of nine tide-gauge to zero. These were: Karachi, Karwar, Bombay, Beypore, Cochin, Nagapattinam, Madras, Vishakhapatnam, and a False point. Since the Indian east and west coasts differ by approximately 35 cm in height, assuming all of them to be zero is at odds with the approach used in other countries which use single tide gauges (e.g., the UK uses Newlyn tide gauge, while North America uses Father's Point at Rimouski, Canada). This has led to a north-south slope in the IVD (e.g., Featherstone and Filmer, 2012 for north-south slope in Australian Height Datum). Another reason for the north-south slope can be the computation of geopotential numbers using normal gravity instead of the actual gravity observations. The slope will not be noticed by practicing land surveyors working in localized areas, but will become perceptible for large-scale projects and when trying to combine GNSS-geoid heights with leveled IVD heights.

A precise leveling was done covering 18000 miles to generate the first leveling net of India. This was started in 1858 and took almost half a century. With the advent of a new relatively sophisticated instrument, another leveling exercise was started in 1914 that comprises 16000 miles. The first leveling network was adjusted following the leveling lines and not the complete Network. Also, the second leveling network was adjusted onto the first Network.

In India, the heights based on 1909 datum were computed by calculating geopotential numbers wherein the Earth's gravity field was replaced by normal gravity (Burrard, 1910), thus producing normal-geopotential or spheropotential numbers (Featherstone and Kuhn, 2006). Later, dynamic and orthometric corrections were applied to give the final heights, but these did not use observed gravity either. The correction term was given by Prof. Helmert in 1884 and then again in 1907. However, as given in 1884, the same formula was used to apply a correction term to avoid confusion and afresh heavy computation. As such, IVD1909 provides heights in the normal-orthometric height system.

Considering the fact that the height system is almost a decade ago and with the availability of precise relative gravimeters, the Survey of India (SoI) started a re-leveling program to modernize the prevailing height system and provide Helmert's orthometric heights. The skeleton leveling network for IVD2009 consists of approximately 500 benchmarks consisting of 29 leveling lines and 31 junction points covering 19,450 linear km. This scrupulous establishment of the high precise leveling networks, in a country like India that consists of several varying landforms, by our national organization is one of its several achievements that is always immensely recognized and appreciated, nationally and internationally.

The geo-potential value for IVD2009 was calculated using data from eight tide gauges: Mumbai, Marmagao, Karwar, and New Mangalore on the western coast, and Paradip, Vishakhapatnam, Chennai, and Tuticorin on the eastern coast. The Zo value, i.e., the difference between the chart datum and the mean sea surface at these eight tidal observatories, ranges from 0.62 m to 2.56 m for the tidal data used from 1976-1994. The local geo-potential value at these eight tidal observatories was computed that varies from 62636856.54 $m^2s^{-2}$ to 62636861.80 $m^2s^{-2}$. However, the reference geo-potential value for IVD2009 was taken as the average of the values and assumed that this average value is the same at all the eight tidal observatories. Therefore, the north-south slope will still be there, but the heights will now be Helmert's orthometric height.

As such, IVD2009 also has scope of improvement after further in-depth analysis. However, due to the non-availability of the details of the IVD computation, it is difficult to further study the merits and limitations of the IVD2009. There are also further complications that MSL is not coincident with the geoid close to coasts due to increased oceanographic phenomena in these areas. However, the conceptual/scientific reasons for these discrepancies do not affect the practicality for the land surveyors in localized areas. Following the suit of New Zealand (LINZ, 2016) and Canada (Véronneau and Huang, 2016), Survey of India is working towards developing a precise gravimetric geoid model for India that is planned to be adopted as the IVDnew, whenever developed. SoI had developed IndGeoid versions alpha and beta, but these are not discussed here due to the non-availability of the information on their methodologies and data in the public domain.

### 4.3 Suggestions/Recommendations

The following members participated in the group meeting on Vertical datum group:

Dr. S. K. Singh, SoI (Retd.)

Prof. Dheeraj Kumar, IIT-ISM

Mr. Varun Kumar, SoI

Dr. A. P. Singh, NGRI,

Dr. Ganesh, ISRO

Dr. Manish Saxena, ISRO

Mr. A. Kartik, ISRO

Dr. I. M. Bahuguna, ISRO

Dr. Ritesh Agrawal, ISRO

Dr. Ashutosh Tiwari, IITK

Mr. Jai Prakash, IIT Kanpur

Mr. Ropesh Goyal, IIT Kanpur

The meeting started with a presentation by Dr. S. K. Singh on Indian Vertical Datum 2009 to provide an overview of the status and fundamental background on 'Vertical datum' to all the participants. After that, the floor was open for discussion. The key points that emerged from the discussions are provided below as the group recommendations for further pursuance:

## 1) Current status of Indian Vertical Datum (IVD)

IVD1909 (Burrard, 1910) and IVD2009 (G&RB, 2018) were developed with the then best available data and strategy. However, there is significant scope of improvement in IVD as per present requirements.

There is a substantial need for a well-established geoid model. Therefore, the new reference datum should rely on GNSS as well as on a gravimetric geoid model.

The direct measurements approach involves the measurement of geoidal undulations at any point on the Earth's surface using the well-established levelling, gravity measurements, and GNSS positioning. This approach is quite accurate but limited to short-area coverage due to obvious limitations of spirit levelling.

The gravimetric approach can be applied to calculate the geoid model from gravity anomaly and can be done using the mixture of data from satellite, airborne, and terrestrial gravimetry.

Once a precise geoid model is made available for an area, the model can be used to transform the GNSS-derived ellipsoidal height to the orthometric height. With precise processing of GNSS data, ellipsoidal heights can be obtained with an accuracy of a few centimeters.

Hence, the availability of a well-established geoid model will help obtain orthometric heights and reference height precisely by GNSS positioning.

We must pursue for IVD20XX.

A working group must be formed to analyze discrepancy and corresponding error propagation in the current IVD.

## 2) Possibility of geoid as a vertical datum

We can follow the suit of New Zealand (LINZ 2016) and Canada (Véronneau and Huang, 2016) to adopt geoid as our vertical datum. It can also be incorporated into CORS stations to have real-time 3D locations.

However, a better option could be to densify, adjust and maintain our levelling network to serve as the national vertical datum. We may then introduce a precise (hybrid) geoid based vertical working surface (similar to AVWS) for various applications. It can also be incorporated into CORS stations to have real-time 3D locations.

It must be a long-term project (5-8 years) where we follow a more rigorous methodology best suited for India. We must aim for precise geoid, including airborne gravity and the latest gravity coverage (not older than 20 years). In the meantime, we can have several test computations of Indian national geoid, but it will not be taken as IVD (something like IndGG-CUT 2021 developed by Goyal et al., 2021b).

It should be a joint project of NCG-IITK, SoI, NGRI, and other organizations. SoI can lead the data procurement. The collected data of the best precision available will be shared with all the participating organizations. Based on the previous experiences, SoI (Singh, 2007; Mishra and Ghosh, 2016; Mishra, 2018; Singh and Srivastava, 2018), NGRI (Carrion et al., 2009; Srinivas et al., 2012) and NCG-IITK (Goyal et al., 2020a, 2021c, 2021d), all have proposed to compute Indian geoid model, it is decided that all organizations will compute Indian geoid with the same data for comparison, something like Colorado project (Wang et al., 2020) or Auvergne quasigeoid comparisons (e.g. Goyal et al., 2021a). A geoid model should be developed at 2'x2' or finer grids. They must share the detailed methodologies that would be adopted for their calculations.

Since India has vast topographical features along with a plethora of geodynamic activities, we might have to develop our algorithms to reduce systematic biases. Because it is quite possible that several assumptions and approximations being followed around the world might not be valid over India, e.g., the divergence of terrain corrections (computed using FFT) in terrain with slope >45degrees (e.g., Goyal et al., 2020b), or some modified method of downward continuation (may be modified inverse Poisson integration). This is important to realize the goal of 5 cm or better accuracy of the Indian geoid model. Research working groups can be formed to study theoretical developments.

**3) Possibility of working and scientific vertical datum**

Yes, we can have two vertical datums: working datum comprises hybrid geoid and is more suitable for engineering applications and surveyors. Geoid is a gravimetric quantity, and therefore the signatures of geophysical/geodynamic phenomenon are somewhat captured in a precise geoid. So, scientific geoid should be purely based on gravimetric data to be used by research organizations. Both can be incorporated with CORS stations and can be selected by users as per their requirement.

**4) Local vs global Geopotential value and consistency with IHRS**

The W0_LVD for IVD2009 (Singh, 2018) was computed with the then best available data and strategy. There is significant scope for calculating new W0_LVD accounting for various systematic biases (cf. Goyal and Featherstone, 2021), e.g., different tide-system, zero-degree correction, precise-high-resolution SST, the possibility of oceanographic MDT.

A detailed study is needed for the comparison of merits and demerits of defining W0 at one location and constraining W0 at number of tide-gauges.

The intermediate and final computations must be in line with IHRS standards.

Moreover, India's present local W0 value has been computed with reference to global W0 (IERS, 2010) = 62636856.00 $m^2s^{-2}$. It must be recomputed with respect to the latest global W0 (Poutanen and Rózsa, 2020) = 62636853.4 $m^2s^{-2}$

**5) Indian participation to IHRF**

Hyderabad and Lucknow are already being proposed (cf. Sánchez et al., 2021). We can also propose to include all our other IGS stations. We should, however, check for the involved terms and conditions.

**6) Ellipsoid for vertical datum and horizontal datum (WGS84 and/or GRS80)**

We must be consistent with a particular ellipsoid, whether GRS80 (Moritz, 1980) or WGS84 (NIMA, 2000). The suggested ellipsoid is WGS84 since it is used for IGRF also.

**7) Standard operating procedure**

SOPs should be prepared with discussions from all the participating organizations with possibly NCG-IITK as the coordinating institute. Also, different user groups' requirements should be taken into account, e.g., geodesists, geophysicists, land surveyors, researchers, etc.

SOP is needed primarily for data collection and processing to avoid/minimize duplication of the data collection.

**8) Adjustment of the datasets**

In IVD1909: Levelling lines were adjusted.

In IVD2009: Levelling network was adjusted.

There is a scope of re-adjustment of the whole leveling network based on the height information, unlike previously when the heights were converted to the geopotential values before adjustment. NCG-IITK can develop the necessary software to be used by G&RB.

NCG-IITK must run a course on the design and adjustment of geodetic control networks.

**9) Advantages/disadvantages of current data sharing policy of BM heights**

Precise data (with the least count of 1 mm) must be shared with research organizations, may be, after introducing/signing a necessary MoU/agreement. It is inevitable to share precise data for research activities. The use of GNSS for leveling should also be explored, something like relative leveling or densification in a local area. These must be further compared with the pure leveling from GTS benchmarks. The same can also be tested with TS.

ISRO can provide expertise in the field of NavIC/GNSS based high precision position and timing receivers.

We should also explore the development of local geometric geoids for local/regional applications.

**10) Way Forward**

NCG-IITK should be approached to a) develop indigenous software and impart training, and b) run courses on the subject.

NCG-IITK can be the coordinating organization.

G&RB can be the lead organization. Development of geoid model must be taken up on priority after collecting all available latest gravity and leveling data available with other departments.

We should identify a group of institutes/organizations with similar interests to come forward and express their potential points for collaboration/participation in different aspects of the needed Redefined IVD (that also includes development of precise model for SST and vertical land motion).

Each participating organization will submit a small write-up on their previous experience which will be collated by NCG-IITK. NCG-IITK will share this report with everyone to discuss the further course of action.

## 5. Gravity datum group

### 5.1. Introduction

Gravitation at any point can be defined as an integral of attraction caused by the solid earth, ocean, atmosphere, moon, sun and other planets as well. Gravity data is an important input for many research work, from defining a vertical datum to earth system and climate change studies. There are several practical uses of precise gravity field and its derivatives necessitating development of a gravity data bank and in-depth knowledge of its multifarious applications. A few of these studies include sea-level rise (Tamisiea et al., 2001), ocean circulation (Marshall, 1985), dynamic ocean topography (Albertella and Rummel, 2014), sea-floor mapping (Cazenave et al., 1986), ice-mass balance (Ivins et al., 2005), deep-mantle convection (Chase, 1979), glacial isostatic adjustment (Root et al., 2015), crustal motion (Vermeersen et al., 2004) and earth rotation (Chao, 1994). Gravity also plays a vital role in almost all geophysical explorations and calculation of satellite orbits (Scharroo and Visser, 1998).

In India, terrestrial and airborne gravity data is being collected for several years by many Government and public organizations to meet the requirements of their respective departments/ organizations and archived. Though the data collection, archival and usage are done, participating organizations have either very restrictive data sharing amongst themselves or with any other scientific user under the pretext of national security or some other considerations. Though these considerations must always receive the top priority, the organizations are neither aware of the accuracy of their data collected and preserved by them nor do they know how it will affect the security of the country.

There are some laid down data dissemination policies by Ministry of Defence (MoD) and Ministry of Science and Technology, Govt. of India, for sharing the gravity data. With changing times and in the era of satellite technology, one can get numerous types of information without extensive fieldwork. Considering the importance of such data for research work and various developmental activities, satisfy aspirations of scientific community and to be part of developing digital India, the policies and restrictions need to be reviewed in light of the DST Guidelines for acquiring and producing Geospatial Data and Geospatial Data Services including Maps (DST F.No.SM/25/02/2020 (Part-I) dated 15th February, 2021).

### 5.2. Problems with existing National Scenario

#### *5.2.1. Non-availability of a well-defined and adjusted National gravity datum*

Currently, Indian gravity base station is situated at Dehradun having a *g* value of 979064 mgal. This base value itself has many discrepancies as mentioned by Gulatee (1959). To prepare the gravity map series of India, the data collected by various agencies were converted to a common datum (Indian National Gravity Base at Dehradun). The absolute gravity value, $g_0$, of the Indian National Gravity Datum (1963) is 978064.0 mGal and that based on IGSN71 (1971) is 978049.09 mGal. It should be noted that values were calculated on the basis of Manghnani and Woollard's N-S calibration line (Manghnani and Woollard, 1963) and were not based on actual IGSN71 calibrated stations in India (GMSI brochure as cited by GETECH, 2006). However, every gravity data collecting, using and archiving organisation claim that their gravity data corresponds to IGSN71 network. There was not even once the data collected by several organisations were combined and adjusted to define a National Gravity network.

Therefore, the aforementioned approach has created a misleading concept on the availability gravity data in the country referring to a single gravity datum.

### *5.2.2. Non-availability of consistent and sharable gravity data*

The gravity data being collected by five authorized institutions/organizations do not come from the same gravimeters. They differ from each other on the basis of accuracy and in particular the drift error. The employed gravimeters have never been calibrated for the drift error after they were bought. Hence, measuring the gravity without accounting for drift error will have low acceptability. Further, no optimal methodology was proposed to merge/compile the heterogenous data (from different gravimeters).

In India, we understand that there two very expensive super conducting gravimeters, one with Wadia Institute of Himalayan Geology, Dehradun, located at Guttu (Mussoorie, Uttarakhand) and the other with Institute of Seismic Research (ISR), Gandhinagar, located in Kutch district. Survey of India, NGRI, Hyderabad and Geological Survey of India are in possession of Absolute gravimeters, but never utilised in setting up of National absolute gravity network. But nobody knows whether these gravimeters are still used to collect the data, and if in working condition, what is the quality of data which is collected by these gravimeters and how they are used in defining the National Gravity Network.

### *5.2.3. Absence of any existing well-defined gravity policy in the country*

Survey of India, the main terrestrial gravity data collector for the whole country and conscience keeper for the Ministry of Defence, holds the policy that “the gravity data with standard deviation less than 5mgal in plain areas and less than 20 mGal in hill areas” will not be shared. When SOI does not have an adjusted gravity network and the quality of its gravity values are unknown, it is not understood how they can find the standard deviation of their observed gravity values.

Similarly, a line in a paper by Sundaram et al. (2006) that says that the Geological Survey of India (GSI) holds the gravity policy that “The gravity data values will be rounded off to 1 mGal for non-restricted areas and 20 mGal for restricted areas.” It is not understood that what has gravity data accuracy to do with restricted and non-restricted areas of a topographical map.

However, at present, when it is claimed that that the Satellite Gravity Gradiometry, GOCE, data is accurate up to 1 mGal with a global coverage (GOCE website), the aforementioned gravity policy doesn’t augur well with the research community. For a researcher, the above policy has no meaning as far as gravity studies are concerned because better gravity data are available in public domain. This restrictive scenario in the country for gravity research and related applications has put undue limitations on data sharing.

The gravity data is “secured” under the name of national security. This situation could have been tolerated if this so called “classified” data is shared only between MoD and SoI. But presently, anyone who has around 50 lakhs, can buy a relative gravimeter and take readings at any location of his/her choice. Hence, there are two serious questions which really need to be answered. First, if the gravity data is classified, why the procurement of gravimeters is not restricted? Second, though national security is always of prime concern, in the prevailing restrictive environment it is important to understand what are the security concerns on sharing the gravity data of unknown quality? Further, the scientific community is curious to learn about the security concerns, when the so called "classified" data of national importance is being sold by some international group (GETECH group at the University of Leeds) and when the oil companies (Maharatna company of India) hire international groups for collecting airborne gravity data.

When the countries around the world are striving to create their national gravity network at micro Gal accuracy, what has been our response? We feel satisfied after providing misleading information on the unknown quality of gravity, imposing undue restrictions on the gravity data, buying gravimeters which are kept closed doors in an underutilized environment, and writing papers on preparing a so-called national gravity policy. Then it is expected that the research should be of highest quality. Such restrictions are the reason that significant component of research in this field is brought from international community to this country because if someone wants to do something new, the biggest hurdle will be caused by existing policies under the garb of national security. Genuine researchers in the country will be always ready to sign any suitable undertaking to take up sensitive research activities on gravity.

### 5.3. Discussion points during the Brain storming Session

The following members participated in the group meeting on Gravity datum group:

1. Dr. U. N. Mishra, Survey of India
2. Col. Arjun Sampath, MO-GSGS
3. Dr. Ashish Shukla, Space Application Centre (SAC)
4. Dr. Nirmala, SAC
5. Shri G. Kannan, RCI
6. Dr M. Sree Ramana, RCI
7. Shri Murali Krishna, RCI
8. Maj Gen (Dr) B,Nagarajan, IIT Kanpur
9. Ms. Drishti Agarwal, IIT Kanpur
10. Shri. Arnab Laha, IIT Kanpur

**Points put up for discussion to the participating Members**

a) Non-availability of consistent National Gravity Datum

b) Gravity Data collection and absence of SOP for gravity data reduction

c) Issues with current scenario of gravity in India (Heterogeneous, non- transparent and non-sharable)

d) Absence of any existing well-defined gravity policy in the country

e) Need of the hour

*5.3.1. Points suggested by Survey of India*

1. Gravity data of Indian land mass can be improved in quality by increasing the density of gravity stations measured by Absolute Gravimeters and then relative gravimeters can be used to provide gravity value of closely spaced stations by closing smaller loops. Organizations like Survey of India, NGRI etc. are already owning Absolute Gravimeters. All these organizations can contribute in this work. However, leadership role has to be given to SoI for data collection, archiving and sharing of gravity data as this premier mapping agency of Govt. of India has performed excellently in this field so far. Scarcity of manpower can always be overcome with govt. support.
2. As per new geospatial data sharing policy, no area within the boundary of India is restricted area anymore. Only some attributes have been put under negative list which will be decided by DST. It is believed that threshold accuracy of 1m horizontal, 3 m vertical and 1 milli gal gravity anomaly is for these negative listed attributes. More clarity is required on this otherwise how 5 cm accurate horizontal positioning will be provided to common man online through CORS which is a reality now. Recently developed Global Geoid Models are providing far more accurate vertical height which are in open domain. The new policy also says that anything which is open globally cannot be restricted in India.

*5.3.2. Points suggested by RCI (Defence Research & Development Organisation)*

1. To establish a National Policy on Gravity data
2. A nodal agency to be identified as the custodian of gravity data
3. All agencies collecting the data to share the same with the nodal agency
4. The quality of data which can be shared to be discussed further to arrive at the values.
5. Gravity data need to be updated.
6. Negative list to be worked out afresh
7. Models to be updated with respect to changing terrain conditions and their validation
8. Collaboration between organizations required to generate the latest gravity data bringing out the synergy of expertise
9. To develop our own gravimeters
10. Data sharing to be controlled by the nodal agency based on the policy to be established.

*5.3.3 Points put forward by Space Application Centre (ISRO)*

Following suggestions are also made on gravity measurements in India:

1. There should be a national policy for gravity data collection and campaigns in India.
2. A lead agency should be identified for this.
3. Gravity mapping/data digitization should be done using a network of stations.
4. Most accurate instruments and vendors for gravity measurements should be identified.
5. A timeline should be fixed to complete the activities and data dissemination policy should be charted out.

#### *5.3.4. Some more points that came up during the discussion*

1. Need to combine the different methods of gravity data collection: Terrestrial, Airborne, Satellite gravimetry
2. Various organizations in India are collecting gravity data. However, the information is restricted within these organizations either due to security or for other reasons.
3. There is no standard operating procedure for computing the gravity anomaly.
4. There should be a lab model for absolute gravity measurement ready by 2023. Prof. Saikat Ghosh from IITK works on cold atom gravimeter.
5. What are the commercial aspects, and what accuracy is needed for the commercial and scientific purpose?
6. What level of accuracy of gravity data can be shared?
7. Need to set up the inventory of gravity measurement equipment available in the country including the nos. of Super conducting gravimeters, Absolute gravimeters, Relative gravimeters that can be used for collection of terrestrial gravity data and no. of aircrafts and airborne gravimeter that are available for data collection.
8. How often should the data need to be updated? We should look for developing a completely automated model.

### 5.4. Need of the hour

Based on the points provided by various organisations participated in the group discussion and also on detailed discussions the following points were flagged as the urgent need of the hour

1. Imposing the restrictions on data can never be questioned, as national security overrides all other activities, but those concerns need to be discussed.
2. With the introduction of new satellites, GOCE and GRACE dedicated for gravity measurements, can give the gravity data accurate up to 1 mGal, amounting to Geoid undulation determination accuracy up to 2-3 cm (EGG-C, 2012), the existing gravity policies need to be revised.
3. The policy of sharing the gravity data, rounded off to a precision of 1 mGal and 20 mGal in unrestricted and restricted areas respectively as mentioned by GSI and also the restrictions imposed by SOI does not appear to be encouraging and justified in the context of gravity field related studies and research in the country when gravity data from GOCE and other satellite based technologies can offer to an accuracy up to 1 mGal.
4. Applying restrictions to the gravity data, an important input for many research works, is a major drawback for the gravity related research works in India. It is inevitable, that all the Government, public and private institutes and organizations dealing with gravity data should come on a common platform and discuss this matter on urgent basis.
5. It is once again emphasised that any genuine earth science researcher in the country will be ready to sign any suitable undertaking to take up sensitive research activities on gravity.

### 5.5. Group Recommendations

**A. To establish a consistent and accurate gravity datum for the country**

1. Need to set up the inventory of gravity measurement equipment available in the country including the nos. of super conducting gravimeters, absolute gravimeters and relative gravimeters that can be used for collection of terrestrial gravity data, and no. of aircrafts and airborne gravimeters that are available for airborne gravity data collection.
2. A consistent and precise National Gravity Network should be established. Available absolute and relative gravimeters along with trained personnel from several organisations and stakeholders can be pooled to form the resource for carrying out the gravity survey. A new gravity observational programme similar to 'GRAV D' programme of USA also can be initiated.
3. Standard operating procedures for gravity data observation, computations and reduction for computing the different types of gravity anomalies and gravity disturbance should be prepared and distributed amongst the different organisations interested in gravity data collection.
4. Need to combine the different methods of gravity data collection: Terrestrial, Airborne, Satellite gravimetry when establishing the National Gravity Network.
5. Collaboration between organizations required to generate the latest gravity data, making use of the expertise available with different organisations.
6. A timeline should be fixed to complete the activities and data dissemination policy should be charted out.

**B. To establish a National Policy on Gravity data**

1. A new National Gravity Policy needs to be formulated for Gravity data collection, archiving and data distribution.
2. A nodal agency should be identified as the custodian of gravity data.
3. All agencies collecting the data to share the same with the nodal agency. Private players can be encouraged to help in speeding up the data collection
4. The quality of data which can be shared to be discussed further to arrive at the values. Gravity values of different accuracies can be thought of and supplied to indenting agencies, based on the application for which it is needed.
5. Gravity data up-dation period cycle needs to spelt out clearly in the policy .

5. Negative list to be worked out afresh
6. Models to be updated with respect to changing terrain conditions and their validation
7. Data sharing to be controlled by the nodal agency based on the policy to be established.

## 6. Tidal datum group

### 6.1. Introduction

Tide gauges provide recordings of the continuous rise and fall of the sea surface and therefore it is a widely used method for studying sea surface topography as well as sea level rise. At sufficiently high frequencies, accurate information about local sea level can be obtained therefore it is highly used for understanding local sea-level change and for investigating phenomena such as storm surges and tsunamis (Gomis et al., 2012). Various countries have developed their tide gauge network and adopted its tidal datum. Tidal datums are employed to provide reference points for determining water levels. The datum is defined by measuring tidal record over a defined period known as Tidal datum Epoch (Blumberg & Bruno, 2018).

### 6.2. International Status

The material for this section has been liberally taken from the cited references given under the list of references for tidal datum (Appendix-II).

In the USA, the National Water Level Observation Network (NWLON) provides standards for tidal datums and water levels. NWLON is a network of long-term, continuously operating water level stations throughout the USA maintained by the Center for Operational Oceanographic Products and Services (CO-OPS). The basic tidal datums commonly used in the USA are Mean Sea Level (MSL), Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Low Water (MLW), Mean Lower Low Water (MLLW), Mean Tide Level (MTL). CO-OPS defined each of these terms with reference to the National Tidal Datum Epoch (NTDE). National Tidal Datum Epoch (NTDE) is 19 years of water level average epoch which was adopted to account for the effect of the 18.6-year cycle of the lunar nodes as well as annual variation in solar declination. The present epoch of NTDE is from 1983 to 2001. To support tidal datum computation from water level data as to benefit the coastal planners and practitioners, CO-OPS has developed a tool named Tidal Analysis and Datum Tool (TAD). This tool allows users to load file of water level data to generate tidal datums https://access.co-ops.nos.noaa.gov/datumcalc/.

In the United Kingdom, the UK National Tide Gauge network was established after severe flooding along the east coast of England. This network consists of 43 tide gauge stations and most of these stations are related to Ordnance Datum Newlyn through levelling network. The Ordnance datum is defined as the average value of sea level recording at the Newlyn tidal observatory for the period of 1915 to 1921. Although ODN is adopted as the national height datum, it could not be adopted universally due to its limitation in accurately transferring height across large stretches of open water (Bradshaw et al. 2015). Therefore, many Islands group adopted their own local datum which are mostly based on assumed mean sea level from 19th Century.

In Australia, the determination of mean sea level (MSL) was achieved through observations at 29 tide gauge stations distributed along the Australian coast from 1966 to 1968. The Australian Height Datum (AHD) Australian height Datum (AHD) was realized by fixing these tide gauge estimates of MSL to zero height value. However, as MSL values are not corrected for the 18.6-year cycle of lunar nodes therefore there exists a difference between MSL and AHD in decimeters. Furthermore, the fixing of multiple tide gauge estimates of MSL values to zero AHD height leads to a north-south slope in the AHD of around a meter (Featherstone and Filmer, 2012).

Along with datum definition, tide gauge stations are backbone in the field of sea level studies. Understanding the current mean sea level trends are essential for understanding the impact of climate science. Tide gauge along the coast measure point wise water level which is used for extracting the mean sea level and extreme events (Pontie et al. 2019). Tide gauge stations along the coast lines are monitored and operated by various national agencies. Data from some these tide gauge stations are archived and freely distributed by international databases. Among these, The Permanent Service for Mean Sea Level (PSMSL) is a global respiratory of long-term sea-level changes based on data received from global tide gauge networks. The monthly and annual mean sea level data from 2000 stations around the world forms the basis of the data set of PSMSL (Holgate et al., 2013). The University of Hawaii Sea Level Center (UHSLC) is a joint research facility of the University of Hawaii and NOAA for collecting, distributing and analyzing the sea level gauge data for climate research. Global Sea Level Observing System (GLOSS) of the Intergovernmental Oceanographic Commission (IOC) has nearly 290 tide gauge stations worldwide and many of which are configured for real time monitoring of rapidly sampled data for Tsunami detection. All these global initiatives related to tide gauge data make it possible for understanding ocean dynamics in terms of global and mean sea level. However, only a fraction of these tide gauge stations is having multi decadal data which is very essential for climate science studies. Furthermore, majority of the tide gauge stations with longest observation history are located in either Europe or North America.

The uneven distribution of tide gauge stations is another issue in quantification and understanding of sea level at the global and regional scale (Jevrejeva et al., 2014; Dangendorf et al., 2017; Pontie et al.2019).

The estimation of sea level rise gets biased by the presence of vertical land motion (VLM) if any of the tide gauge benchmark. The Earth's surface upon which the tide gauge benchmark is situated also undergoes deformation due to tectonics and hydrological mass change in regional as well as local scale. Therefore, precise estimation of VLM is essential to estimate sea level with accuracy. To constrain the vertical land motion, one best option is to deploy continuous Global Navigational Satellite Systems (GNSS) station which can determine the land motion with good repeatability. However, shorter span of GNSS data comparing to the tide gauge observation history and reference frame related errors of GNSS derived estimates are limitations of GNSS based VLM (Pontie et al.2019).

### 6.3. National Status

In India, Tide Gauge stations have been employed along with the costs of India by various Indian Institutions such as Survey of India (SOI), Indian National Centre for Ocean Information Services (INCOIS) as well as National Institute of Ocean Technology (NIOT). Data from these stations have been used for various research purposes.

SOI with its long history of maintaining tidal data is actively working on publication of INDIAN TIDE TABLE which comprises of tidal prediction of 76 Indian and foreign ports which are mainly for navigational activities. It also provides tidal prediction for any place along the Indian coast to the various Government and private agencies on demand. Furthermore, SOI is also involved with the determination of mean sea level. After 2004 Tsunami, SOI modernized and expanded the Tide gauge network across the country. During this course of time, SOI established 36 digital tide gauge stations collocated with dual frequency Global Positioning Receivers along the Indian coastlines and Islands. NIOT also within this Indian Tsunami Early warning system has installed 14 real time tide gauge stations. GPS stations are employed in order to differentiate the vertical land motion and sea level rise. The data generated are obtained in real time through satellite communication at INCOIS-Hyderabad, SOI-Dehradun and at NIOT Chennai simultaneously for processing and interpretation.

The mean sea level data from tide gauges are used for investigating regional sea level rise. Below few of the studies of Indian researchers using tide gauge data are illustrated.

Unnikrishnan et al. (2004) analyzed extreme sea level using hourly tide gauge data from three stations located at Paradip, Vishakhapatnam, and Chennai. They identified two to four storm surge events on an average during the period of observation 1974–1988. Highest number of events were occurred in Vishakhapatnam followed by Paradip and the least in Chennai. This study also estimated return period of extreme se level events using statistical analysis and this result is very useful for the design of offshore structure and sea wall. Furthermore, this study realized the need of more closely spaced tide gauge stations for monitoring storm surges as well as improving the return period of extreme sea level events. The 100-year return levels for Paradip, Vishakhapatnam, and Chennai are 4.9m, 2.5m, and 2.0 m, respectively. Finally, this study suggested to opt for numerical models to estimate the return period for regions where tide gauge data is not available.

Unnikrishnan and Shankar (2007) used tide gauge data from the north Indian Ocean and observed low frequency sea level variability within the basin. Th estimates of linear trends at the stations having more than 40 years of observation are in the same range as that of global range. Their estimation of sea level rise was within the range of 1.06– 1.75 mm $yr^{-1}$, with an average of 1.29 mm/yr. Their methodology includes, checking the interstation consistency of sea level records of stations that have at least 20 years of observation records. The stations that passed the consistency test and having more than 40 years observation records were then used for estimating the sea level trends. In the last step, they have corrected the effect of vertical land motion using ICE-5G GIA model (Peltier, 2001, 2004). However due to absence of collocated Global Positioning System (GPS) station, they could not account for the local surface deformation. For this reason, within this study they excluded the stations that are located in tectonically active regions.

Chaudhury and Behera (2015) studied the changes in Mean Sea Level (MSL) in regional scale using data from tide gauge stations that are situated along the north Indian ocean as well as using satellite altimetry data. It is observed from this study that most of the tide gauge station show positive trend in the sea level. The estimates of the trend of MSL at few places are in consistent with the global estimates whereas some of the tide gauge stations show unusual behavior. It is reported in this study that, there exist a regional and local variation of MSL. This study recommends further investigation about such regional and local variations of MSL in order to understand individual behavior of each region concerning the impact of climate change. Furthermore, this study realized that only analyzing available data is not enough and there needs a proper hydrodynamics modelling on finer scale to decipher the dynamics and local variability of MSL due to climate change.

### 6.4. Discussion and Recommendations

The following members participated in the group meeting on Tidal datum group:

1. Dr. Rashmi Sharma
2. Dr. Sharad Chander
3. Dr. Sreejith
4. Dr. Vamsi

5. Dr. R S Mahendra
6. Dr. Sudheer Joseph
7. Dr. Sunanda
8. Shri Subash Kumar
9. Digvijay Singh
10. Dr. Balaji Devaraju

Discussion session for the sub-group on Tidal datum was held in a Webex breakout conference room.

The overall idea of the discussion was to discuss current practices and future perspectives for defining a Tidal datum, and to understand how it can be adopted for use to different agencies. The meeting participants had research interests in the area of satellite altimetry, coastal studies, marine geodesy, chart datum and GNSS for Tsunami early warning system. The following points were discussed:

Dr. Rashmi discussed altimetry applications for coastal studies, highlighting the effect of associated errors, particularly due to the contamination of the altimeter. She emphasized that there is a lack of reference stations in coastal areas. Although global altimetry products are easily available, validity of coastal sea level observations from altimeters is a major bottleneck, since for validation, the tide gauges need to be equipped with GPS/ NaVIC receivers. The tidal stations do not have co-located GPS, leading to difficulties in correcting for land movement. The unavailability of GNSS station is a problem especially affecting the coastal sea level observations. Dr. Rashmi also highlighted that there is non-uniformity in coastal sea level rise for different coasts of India. Correcting land movement from altimeter data is not done. It was recommended that GNSS and NAVIC receivers should be co-located to the tide gauges. This will help in long term monitoring of the sea level for coastal areas and will also be helpful for the surface water and ocean topography (SWOT) mission, which covers a much larger swath. A co-located GNSS site at every tide gauge may be extremely useful in this regard.

Dr. R S Mahendra discussed that his research group at INCOIS works on 2D and 3D geospatial data pertaining to images, maps and thematic layers pertaining to the coasts and oceans. 3D-DEM and bathymetry. He emphasized the requirement of consistency of the chart datum. He gave an example that they have some data surveyed, pertaining to MSL corrected datum. However, open access data uses WGS84 datum, and the national hydrographic office (NHO) gives data which follows the chart datum. This brings challenges for bringing observations in a common reference frame using metadata information and merge. Validation of vertical benchmarks is also required. He recommended design of a common reference framework for both horizontal and vertical observations and suggested that Survey of India (SoI) should make their common datum benchmarks available in an open domain. If there are restrained datasets, SoI can share it to national organizations to have a common matching geospatial data, that facilitates usage for all organizations. This can be seamlessly followed across the country.

Dr. Sharad Chadra discussed issues related to his work on the quantification of total freshwater discharge in the ocean volume variation. He mentioned that altimetry data uses WGS84, which is converted to EGM2008 or to mean sea surface. However, most of the central water commission (CWC) stations are far away (80 to 100 km) and are in a different datum, which brings difficulty in quantifying the comparison of discharge. He also recommended a standard reference frame for both horizontal and vertical observations. Prof. Balaji clarified that we now refer to 3D reference system as the geometric reference system and the vertical reference frame as a physical reference frame. Another recommendation was to set up a strong reference for run-off gauges, which will help in validating altimetry observations. This will particularly be useful for the datasets from the upcoming SWOT mission.

Dr. Sreejith discussed his work on satellite altimetry to derive mean sea surface and to investigate ways in which it can be tied to the tide gauge data. He suggested tide gauges co-located with a GNSS station to enable this linkage. He highlighted that the geophysical geoid does not have good accuracy and told that a local geoid can be linked to the tide gauge observations, for which the minimum requirement is tide gauge station with GNSS. He discussed that they have developed a marine geoid, but it has intrinsic problems near the coast. Dr. Rashmi further added that India has its own altimeter SARAL-AltiKa. AltiKa is in a drifting phase orbit, and we have very fine spatial resolution altimeter tracks, suitable for geoid determination. Some work aimed at improving the resolution of the AltiKA measurements was discussed. Another recommendation was that for oceanography also, the altimetric measurements need to be tied to the GNSS stations.

Another major issue discussed was regarding the missing satellite-based observations near the coast, which vary depending on instruments. AltiKA (Ka band) can come as close to 3-4 km. Sentinel altimeter (Ku band) can go closer, but not as close as AltiKA. SWOT dataset resolution will be 2 km, but in that case too, it cannot go closer than 6 km.

Mr. Subhash Kumar discussed that from a user perspective, we do not have a tide gauge network co-located with GNSS. INCOIS and SoI are trying to have a good tide gauge network. Since the mandates are different, we have MSL benchmarks near the tide gauges, and we connect the local benchmarks with tide gauges to compute the chart datum. We have not tied the tide gauges with geoid heights and need to define how a relation can be set up between MSL height and how we can tie the tide gauge with geoid heights.

Dr. Sudip Joseph discussed the vitality of increasing the number of tide gauge stations, emphasizing that it will be helpful for early detection of tsunami waves, and will also have larger coverage. Another issue raised was regarding the use of 19-year epoch by NOAA, highlighting that there can be significant change in the sea level since tide gauge datums keep changing because of land motions. Some examples were talked about, e.g. Gulf of Mexico using 5 year epochs. At SoI, there are scheduled tidal observations at one day, 5 days, 29 days and 5 years. Dr. Joseph recommended that for tsunami observations, spatial frequency of tide gauges can be increased. Most of the tide gauge stations are along the coast. Dr. Vamsi also talked regarding co-location of tide gauge stations using GNSS.

Dr. Rashmi discussed that for the open ocean, no specific requirements are there for a tidal datum. She discussed her research work in ocean modelling at SAC ISRO and told that the altimeter derived sea level is used in the circulation model and altimeter derived wave height in the wave model to see the impact in the open ocean and coastal regions. The work is done in tandem with INCOIS. Data assimilation is done for observations of the open ocean. A common reference surface is generated from model assimilation, mean is subtracted and the data is assimilated. For the open ocean, we do not see any issues regarding the datum. Dr. Vamsi suggested that a proper mean sea surface would be helpful.

There are sea level data available from ESA (Climate Change Initiative product) giving global sea level trend for all coasts. But the problem comes while validation since we wish to detect mm level changes. Unless the tide gauges are assisted with GNSS, utility of these products are not maximized.

***Synergies among geodesy, coastal and oceanographic community***

Another major discussion was about understanding the synergies among geodesy, coastal and oceanographic communities. Dr. Sharad said that we need a continuous reference frame where we can talk on a similar level while measuring a reservoir, water level, total water discharge. He said that we need to look at the ocean mouth and observe tide gauge measurements, their number, quantification accuracy with respect to terrestrial observations. He suggested that consistency is required in the coastal region, and we need high resolution dataset where we can transfer information gathered from the previous section.

Dr. Rashmi suggested that going from the ocean to the coast to the inland, it is important to come up with a common reference or datum that seamlessly connects the three regions. She suggested that we can select a test site where we can just test our methodology, put forth a framework to come up with a reference datum surface, mean sea surface and can just showcase for a particular region at a river mouth so that we can include the inland river water region also. She recommended a pilot study for a seamlessly connected datum, which can later be scaled up for the other coastal regions. When working on SWOT (simulated dataset), in the initial six months of the launch, SWOT will be in a rapid orbit, one in the Arabian sea and one in the Bay of Bengal. It would be nice to select a region that falls within the SWOT swath. It can also help the international community since we would give feedback on how SWOT is performing. We can have a unified approach where we put all datasets, develop models and check its applicability and utility.

Mr. Subhash Kumar highlighted that we have a lot of infrastructure in place. There is infrastructure with SoI, and INCOIS. We need to identify sites where we can set up GNSS, tide gauges, current meters, which can give an idea of how we can bring synergy. He also discussed the procedure followed by SoI for determining the mean sea level: SOI has tide gauge stations and then they do periodic observations also at a spacing of 80 km to define the MSL. They observe MSL data for 29 days and then they come up with a backward calculation to determine the local MSL at that place. This process is done at every 80-100 km and this is how they have computed local MSL and for the entire country. In this process, they used 19 year data assuming that diurnal process of the moon takes 19 years. But when SoI started gravity observations and levelling measurements, and when they tried to connect some benchmarks in the east to those in the west, there were mismatches (30-35 cm). This is why gravity observations are required and to co-locate it with GPS. He also informed that tidal applications are based on chart datum (where the water level does not go beyond (below) that level), which also differs from port to port. Defining chart datums also requires geodetic linkage, and if we have some altimetry data, and combine these, we can have a more reliable chart datum.

Another issue raised by Prof. Balaji was regarding data sharing practices. An example on ARGO (a multi-organizational program) was discussed. For the Indian ocean, more than 600 ports contributed and shared data publicly. All nations agreed that they would not be holding data. All data was shared. This had advantages related to better assimilation of ocean models, valuable publications.

### 6.5. Overall group recommendations

Based on the discussions, the following recommendations were unanimously put forward by the meeting participants:

1. All participants agreed that we have issues with reference frames and their consistency and suggested that we need a seamless reference frame (geometric/physical), from ocean to the land.
2. Tide gauge stations need to be co-located with GNSS stations.
3. For oceanography also, the altimetric measurements need to be tied to the GNSS stations.
4. Data sharing is also a serious issue and is a big challenge. We can learn from the ARGO program and set up standard guidelines for open data availability.
5. Since we are talking of a national tidal datum, densification of the tidal network and its co-location with GNSS stations is recommended. This will help serve the user community.
6. For better tracking of tsunami waves, spatial frequency of tide gauges can be increased.
7. A precise mean sea surface should be realized using tidal observations.
8. Dedicated altimetry Cal/Val sites over the Indian ocean can be set up.

## Appendix-I: Programme Schedule

| Time | Activity | Speaker |
|---|---|---|
| **Day 1: May 6, 2021; Thursday** | | |
| 0915 – 0930 | Welcome address | Dr. Onkar Dikshit |
| 0930 – 1000 | Indian National Geodetic Reference Frame - The Concept | Dr. B. Nagarajan |
| 1000 – 1015 | Indian National Geodetic Reference Frame – DST's view | Shri P.S. Acharya (Head, National Geospatial Programme; Head & CEO National Spatial Data Infrastructure, DST) |
| **Introductory presentations** | | |
| 1020 – 1035 | Survey of India | Dr. U. N. Mishra (DSG, North Zone, Survey of India) |
| 1035 – 1050 | National Geophysical Research Institute | Dr. V. M. Tiwari (Director, NGRI) |
| 1105 - 1120 | Defence Research and Development Organization | Shri. M Kannan (Scientist 'G', RCI Lab, DRDO) |
| ***Tea Break: 1120-1130*** | | |
| 1130 - 1145 | Importance of geodetic ties for sea-level monitoring | Dr. M. Ravichandran (Director, NCPOR) |
| 1145 - 1200 | Reliable and sustainable sea level measurement | Dr. G. A. Ramadass (Director, NIOT) |
| 1200 - 1215 | Sea Surface/Dynamic Topography using Radar Altimeter | Dr. Raj Kumar (Director, NRSC) |
| 1215 - 1230 | INCOIS Sea level and GNSS networks for Ocean Hazard applications | Dr. Srinivasa Kumar (Director, INCOIS) |
| 1300 - 1315 | Military Survey – GSGS (Comments) | Brig. Arun (Addl. Director General, MO-GSGS) |
| 1315 - 1330 | Summary and programmatic of group discussion | Dr. Balaji Devaraju |
| ***Lunch Break: 1330-1430*** | | |
| 1430 - 1630 | Group discussion on the themes in respective discussion rooms | Participants |
| ***Tea Break: 1630-1645*** | | |
| 1645 - onwards | Group discussion to continue including preparation of group resolutions and PPT | Participants |

| **Day 2: May 7, 2021; Friday** | | |
|---|---|---|
| 0930 - 1000 | Presentation by Gravity datum group | Group representative |
| 1000 - 1030 | Presentation by Horizontal datum group | Group representative |
| 1030 - 1100 | Presentation by Vertical datum group | Group representative |
| 1100 - 1130 | Presentation by Tidal datum group | Group representative |
| ***Tea Break: 1100-1145*** | | |
| 1145 - 1300 | Summarizing the discussions and drafting of final recommendations | Dr. B. Nagarajan |

**List of participants**

| **Participant** | **Organization** | **Email id** |
|---|---|---|
| **Horizontal Datum Group** | | |
| Dr. Onkar Dikshit, Convener | IIT Kanpur | onkar@iitk.ac.in |
| Dr. Ashok Kumar Singh | DST | ashokk.singh@nic.in |
| Dr. Nitin Joshi | Survey of India (SoI) | nitin.joshi.soi@gov.in |
| Dr. Kaushik R. V. | ISRO | kaushik@isro.gov.in |
| Dr. D. Ram Rajak | ISRO | rajakdr@sac.isro.gov.in |
| Dr. John Mathew | ISRO | john_mathew@isro.gov.in |
| Dr. Nishkam Jain | ISRO | nishkamjain@sac.isro.gov.in |
| Dr. Ruban Jacob | Geospatial Infrastructure | ruban@geospatialworld.net |
| Dr. Jagat Dwipendra Ray | IIT Kanpur | jagatd@iitk.ac.in |
| Ms Sujata Dhar | IIT Kanpur | sujata@iitk.ac.in |
| **Vertical Datum Group** | | |
| Dr. S. K. Singh, Convener | SoI (Retd.) | sks.19dec@gmail.com |
| Prof. Dheeraj Kumar | IIT-ISM | dheeraj@iitism.ac.in |
| Mr. Varun Kumar | SoI | g.varun.soi@gov.in |
| Dr. A. P. Singh | NGRI | apsingh@ngri.res.in |
| Dr. Ganesh | ISRO | ganesht@istrac.gov.in |
| Dr. Manish Saxena | ISRO | msaxena@isro.gov.in |
| Mr. A. Kartik | ISRO | akartik@ursc.gov.in |
| Dr. I. M. Bahuguna | ISRO | imbahuguna@sac.isro.gov.in |
| Dr. Ritesh Agrawal | ISRO | ritesh_agrawal@sac.isro.gov.in |
| Dr. Ashutosh Tiwari | IIT Kanpur | atiwari@iitk.ac.in |
| Mr. Jai Prakash | IIT Kanpur | jaipr@iitk.ac.in |
| Mr. Ropesh Goyal | | rupeshg@iitk.ac.in |
| **Gravity Datum Group** | | |
| Maj Gen (Dr) B. Nagarajan, Convener | IIT Kanpur | nagaraj@iitk.ac.in |
| Dr. U. N. Mishra, Survey of India | SoI | un.mishra.soi@gov.in |
| Col. Arjun Sampath | MO-GSGS | arjun.sampath.soi@gov.in |

| | | |
|---|---|---|
| Dr. Ashish Shukla | ISRO | ashishs@sac.isro.gov.in |
| Dr. Nirmala | ISRO | nirmalas@ursc.gov.in |
| Shri G. Kannan | RCI | kannan.m@rcilab.in |
| Dr M. Sree Ramana | RCI | sree_mn@yahoo.com |
| Shri Murali Krishna | RCI | muralikrishna.g@rcilab.in |
| Ms. Drishti Agarwal | IIT Kanpur | drishti@iitk.ac.in |
| **Tidal Datum Group** | | |
| Dr. Balaji Devaraju, Convener | IIT Kanpur | dbalaji@iitk.ac.in |
| Dr. Rashmi Sharma | ISRO | rashmi@sac.isro.gov.in |
| Dr. Sharad Chander | ISRO | schander@sac.isro.gov.in |
| Dr. Sreejith, Scientist | ISRO | sreejith@sac.isro.gov.in |
| Dr. Vamsi, Scientist | ISRO | vamsikv@isac.gov.in |
| Dr. R S Mahendra | INCOIS | mahendra@incois.gov.in |
| Dr. Sudheer Joseph | INCOIS | sjo@incois.gov.in |
| Dr. Sunanda, Scientist | INCOIS | sunanda@incois.gov.in |
| Shri Subash Kumar | Trimble | subhash_kumar@trimble.com |
| Mr. Digvijay Singh | IIT Kanpur | sdigvijy@iitk.ac.in |

**Bibliography related to terminology used in Geodesy:**

For various terminology related to Geodesy, please refer to the following links:

1 https://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml

2 https://geodesy.noaa.gov/PUBS_LIB/Geodesy4Layman/toc.htm

3 https://repository.library.noaa.gov/view/noaa/2827/noaa_2827_DS1.pdf?

**Horizontal Datum**

1. Altamimi, J. (2018) From Global to National Geodetic Reference Frames: how are they connected and why are they needed? *The United Nations World Geospatial Information Congress*. Accessible from: http://ggim.un.org/unwgic/presentations/4.5-Zuheir_Altamimi.pdf.
2. Blick, G. (2014) *Reference Frames in Practice Manual*, Commission 5 Working Group 5.2 Reference Frames.
3. Bosy, J. (2014) Global, Regional and National Geodetic Reference Frames for Geodesy and Geodynamics, *Pure Appl. Geophys*. 171 (2014), 783–808.
4. Bruyninx, C. (2009) The European Reference Frame: Maintenance and Products, Geodetic Reference Frames, *International Association of Geodesy Symposia* 134, DOI 10.1007/978-3-642-00860-3_20.
5. Bruyninx, C., Legrand, J., Fabian, A. and Pottiaux, E. (2019) GNSS metadata and data validation in the EUREF Permanent Network. *GPS Solutions*, 23(4), 1-14.
6. Dawson, J. (2015) Geodetic Reference Frame: Australia, *Commonwealth of Australia (Geoscience Australia)* 2015.
7. Dostal, J. (2018) Geodetic Activities in Germany, *PosKEN Workshop*, 26-27 October 2018.
8. Drewes, H. (2017) Frequent epoch reference frames instead of instant station positions and constant velocities, *SIRGAS Symposium*, Argentina, 27-29 November 2017.
9. Gross, R., Beutler, G., and Plag, H. P. (2009) Integrated scientific and societal user requirements and functional specifications for the GGOS, in *Global Geodetic Observing System. Meeting the Requirements of a Global Society on a Changing Planet in 2020,* Plag H. P., Pearlman M. (Eds.) Springer Verlag.
10. Habrich, H. (2007) Realisation of ETRS89 in German State Survey, *EUREF TWG*, Paris, France, 29-30 November 2007.
11. Lee, Y. J., Lee, H. K., Jung, G. H. (2006) Realization of New Korean Horizontal Geodetic Datum: GPS Observation and Network Adjustment, *Proceedings of the Korean Institute of Navigation and Port Research Conference*, v.1, 529-534.
12. National Geodetic Survey. (2018) Horizontal and Geometric Datums, Accessible from: https://www.ngs.noaa.gov/datums/horizontal/index.shtml.
13. Plag, H. P. (2006) *National Geodetic Infrastructure Current Status and Future Requirements:*

*The Example of Norway*, Nevada Bureau of Mines and Geology, Bulletin 112

14. National Research Council. (2010) Precise Geodetic infrastructure National Requirements for a Shared Resource (2010) The National Academies Press Washington, D.C. DOI: https://doi.org/10.17226/12954.
15. Snay, R. A. and Soler, T. (2008) Continuously Operating Reference Station CORS: History, Applications, and Future Enhancements, *Journal of Surveying Engineering*, *ASCE*, DOI: 10.1061/(ASCE)0733-9453(2008)134:4(95).
16. Vanicek, P., Wells, D. E. (1974) Positioning of horizontal geodetic datums, *The Canadian Surveyor*, Volume 28 issue 5 1974.
17. Peng, Z., Li, Zhicai., Hanjiang, W. (2012) Modernization of National Geodetic Datum in China, *Nineteenth United Nations Regional Cartographic Conference for Asia and the Pacific*, Bangkok, 29 October – 1 November 2012.

**Vertical datum**

1. Amos, M. J. (2007) Quasigeoid modelling in New Zealand to unify multiple local vertical datums. PhD thesis. Curtin Univeristy of Technology, Australia.
2. Burrard, S. (1910) Levelling of precision in India. The Great Trigonometrical Survey of India, Vol XIX. Survey of India, Dehradun, India.
3. Carrion, D., Kumar, N., Barzaghi, R., Singh, A.P., Singh, B. (2009) Gravity and geoid in South India and their comparison with EGM2008. Newton's Bulletin 4, 275-283.
4. Featherstone, W.E., Filmer, M.S. (2012) The north-south tilt in the Australian height datum is explained by the ocean's mean dynamic topography. *Journal of Geophysical Research* 117, C08035. https://doi.org/10.1029/2012JC007974
5. Featherstone, W.E., Kuhn, M. (2006) Height systems and vertical datums: A review in the Australian context. Spatial sciences 51, 21-41. https://doi.org/10.1080/14498596.2006.9635062
6. Geodetic and Research Branch, Survey of India (2018) Report on Redefinition of Indian Vertical Datum IVD 2009. Survey of India, Dehradun, India.
7. Goyal, R., Ågren, J., Featherstone, W.E., Sjöberg, L.E., Dikshit, O., Balasubramanian, N. (2021a) Empirical comparison between stochastic and deterministic modifiers over the French Auvergne geoid computation test-bed. *Survey Review*. Online first. https://doi.org/10.1080/00396265.2021.1871821
8. Goyal, R., Featherstone, W.E. (2021b) Subtle considerations in the low degree spherical harmonics synthesis of static and time-varying gravity field models. Submitted. *Journal of Geodesy*.
9. Goyal, R., Featherstone, W.E., Claessens, S.J., Dikshit, O., Balasubramanian, N. (2021c) Indian gravimetric geoid modelling using Curtin University's approach. Submitted. *Terrestrial, Atmospheric and Oceanic Sciences*.
10. Goyal, R., Featherstone, W.E., Claessens, S.J., Dikshit, O., Balasubramanian, N. (2020a) Indian Gravimetric Geoid Model: data, methods and a preliminary test using Curtin University's approach. In: First Asia-Pacific geoid workshop for International Association of Geodesy Sub-Commission 2.4e. Oct 2020. (Taiwan and Virtual)
11. Goyal, R., Featherstone, W.E., Claessens, S.J., Dikshit, O., Balasubramanian, N. (2021d)

Indian gravimetric geoid model: IndGG-CUT2021. In: International Association of Geodesy Scientific Assembly 2021, Beijing, China (virtual)

12. Goyal, R., Featherstone, W.E., Tsoulis, D., Dikshit, O. (2020b) Efficient spatial-spectral computation of local planar gravimetric terrain corrections from high-resolution digital elevation models. *Geophysical Journal International* 221, 1820–1831. https://doi.org/10.1093/gji/ggaa107
13. Hanjiang, W. (2012) Modernization of national geodetic datum in China. In: Nineteenth United Nations Regional Cartographic Conference for Asia and the Pacific, Bangkok.
14. ICSM (2021) Australian Vertical Working Surface (AVWS) technical implementation plan, version 1.4. Available at: https://www.icsm.gov.au/sites/default/files/2021-02/AVWS%20Technical%20Implementation%20Plan_V1.4_0.pdf
15. LINZ (2016) New Zealand Quasigeoid 2016 (NZGeoid2016). Retrieved from: https://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/vertical-datums/new-zealand-quasigeoid-2016-nzgeoid2016
16. Mishra, U.N. (2018) A comparative evaluation of methods for development on Indian geoid model. PhD thesis. IIT Roorkee, India.
17. Mishra, U.N., Ghosh, J.K. (2016) Development of a gravimetric geoid model and a comparative study. *Geodesy and Cartography*, 42, 75-84. https://doi.org/10.3846/20296991.2016.1226368
18. Moritz, H. (2000) Geodetic Reference System 1980. Journal of Geodesy 74, 128–133. https://doi.org/10.1007/s001900050278
19. NIMA (2000) World Geodetic System 1984, its definition and relationships with local geodetic systems. Report TR8350.2, 175 pp. Bethesda, MD, USA. https://earth-info.nga.mil/GandG/publications/tr8350.2/wgs84fin.pdf
20. NRCan (2021) Spatial reference system updates. https://www.nrcan.gc.ca/maps-tools-and-publications/tools/geodetic-reference-systems/height-reference-system-modernization/9054
21. Poutanen, M., Rózsa, S. (2020) The Geodesist's Handbook 2020. *Journal of Geodesy* 94**,** 109. https://doi.org/10.1007/s00190-020-01434-z
22. Richards, D. (2011) Modernization of the Canadian height reference system. Available at: http://www.apegm.mb.ca/pdf/PD_Papers/CdnHeightReferenceSystemModernization2011-01-20.pdf
23. Sánchez L, Ågren, J., Huang, J., Wang, Y.M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G.S., Ahlgren, K., Liu, Q. (2021) Strategy for the realisation of the International Height Reference System (IHRS). *Journal of Geodesy* 95, 33. https://doi.org/10.1007/s00190-021-01481-0
24. Savinykh, V.P., Kaftan, V.I. (2019) National report for the IAG of the IUGG 2015-2018. Geoinformatics research papers, BS7003. https://doi.org/10.2205/2019IUGG-RU-IAG
25. Singh, S.K. (2007) *Determination of high resolution of Indian geoid for GPS levelling*. PhD thesis. IIT Roorkee, India.
26. Singh, S.K. (2018) Towards a new vertical datum for India. In: FIG Congress 2018, Istanbul, Turkey. https://fig.net/resources/proceedings/fig_proceedings/fig2018/papers/ts06e/TS06E_singh_9497.pdf

27. Singh, S.K., Srivastava, R. (2018) Development of geoid model-a case study on western India. In: FIG Congress 2018, Istanbul, Turkey. https://www.fig.net/resources/proceedings/fig_proceedings/fig2018/papers/ts06e/TS06E_singh_srivastava_9496.pdf

28. Srinivas, N., Tiwari, V.M., Tarial, J.S., Prajapti, S., Meshram, A.E., Singh, B., Nagarajan, B. (2012) Gravimetric geoid of a part of south India and its comparison with global geopotential models and GPS-levelling data. Journal of Earth System Science 121, 1025-1032. https://doi.org/10.1007/s12040-012-0205-7

29. Véronneau, M., Huang, J. (2016) The Canadian Geodetic Vertical Datum of 2013 (CGVD2013). *GEOMATICA* 70(1), 9–19. https://doi.org/10.5623/cig2016-101

30. Wang, Y.M., Sánchez, L., Ågren, J., Huang, J.L., Forsberg, R., Abd-Elmotaal, H.A., Barzaghi, R., Bašić, T., Carrion, D., Claessens, S., Erol, B., Erol, S., Filmer, M., Grigoriadis, V.N., Isik, M.S., Jiang, T., Koç, Ö., Li, X.P., Ahlgren, K., Krcmaric, J., Liu, Q., Matsuo, K., Natsiopoulos, D.A., Novák, P., Pail, R., Pitonák, M., Schmidt, M., Varga, M., Vergos, G.S., Véronneau, M., Willberg, M., Zingerle, P. (2020) Colorado geoid computation experiment—Overview and Summary. Submitted. Journal of Geodesy

31. Zilkoski, D.B., Richards, J.H., Young, G.M. (1992) Results of the general adjustment of the North American Vertical Datum of 1988. *Surveying and Land Information Systems* 52, 133-149.

**Gravity datum**

1. Albertella, A. and Rummel, R. (2014) *GOCE geoid, mean dynamic ocean topography and geostrophic velocities*. Report for Centre of Geodetic Earth System Research. Report No. 6.

2. Cazenave, A., Dominh, K., Allegre, C. J., and Marsh, J. G. (1986) Global relationship between oceanic geoid and topography. *Journal of Geophysical Research*, 91, B11, 11439–11450. doi:10.1029/JB091iB11p11439.

3. Chao, B. F. (1994) The Geoid and Earth Rotation. In: *Geophysical Interpretations of Geoid*, eds. P. Vanicek and N. Christou. CRC Press, Boca Raton.

4. Chase, C.G. (1979) Subduction, the geoid, and lower mantle convection. *Nature*, Vol 282, 464-468.

5. Ivins, E.R., Rignot, E., Wu, X., James, T.S., Casassa, G. (2005) *Ice mass balance and Antarctic gravity change: Satellite and terrestrial perspectives*. In: Earth Observation with CHAMP. Springer, pp. 3–12.

6. European GOCE Gravity Consortium (EGG-C). (2012) *GOCE High Level Processing Facility Technical Note*, Report no. GO-TN-HPF-GS-0296.

7. Kulkarni, M.N. (2010) Availability and accessibility of geodetic data in India. *Geospatial World* [online], December, 2010. Available from: https://www.geospatialworld.net/article/availability-and-sccessibility-of-geodetic-data-in-india/ [Accessed August 14, 2017].

8. Manghnani, M.H., Woollard, G.P. (1963) Establishment of north-south gravimetric calibration line in India. *Journal of Geophysical Research*, 68, 6293–6301.

9. Marshall, J.C. (1985) Determining the ocean circulation and improving the geoid from satellite altimetry. *Journal of Physical Oceanography*, 15, 330-349.

10. Mathur, S.P. (1969) *Standardization of gravity and Bouguer anomalies in India*. Thesis (PhD). University of Hawaii. http://hdl.handle.net/10125/11307.

11. Root, B.C., Van der Wal, W., Novák, P., Ebbing, J., Vermeersen, L.L.A. (2015) Glacial isostatic adjustment in the static gravity field of Fennoscandia. *Journal of Geophysical Research*, 120, 503–518. doi:10.1002/2014JB011508.

12. Scharroo, R., and Visser, P. (1998) Precise orbit determination and gravity field improvement for the ERS satellites. *Journal of Geophysical Research*, 103, C4, 8113–8127. doi:10.1029/97JC03179.

13. Srinivas, N., Tiwari, V. M., Tarial, J. S., Prajapti, S, Meshram, A.E., Singh, B, Nagarajan, B. (2012) Gravimetric geoid of a part of south India and its comparison with global geopotential models and GPS-levelling data, *J. Earth Syst. Sci*., 121, No. 4, August 2012, 1025–1032.

14. Sundaram, R.M., Surendranath, M., Reddy, USAN. (2009) Revised gravity maps of India (2006 series)- A cartographic perspective. *Geospatial World* [online], Spetember, 2009. Available from: https://www.geospatialworld.net/article/revised-gravity-maps-of-india-2006-series-a-cartographic-perspective/ [Accessed August 14, 2017].

15. Tamisiea, M. E., Mitrovica, J.X., Milne, G.A. and Davis, J.L. (2001) Global geoid and sea level changes due to present-day ice mass fluctuations. *Journal of Geophysical Research*, 106, B12, 30849–30863. doi:10.1029/2000JB000011.

16. Tiwari, V.M., Veenadhari, B., Gahalaut, V.K., Mukherjee, S., Dimri, V.P. (2014) Gravity, GPA and Geomagnetic Data in India. *Proceedings of the Indian National Science Academy* 80, 705. doi:10.16943/ptinsa/2014/v80i3/55145.

17. Vermeersen, L.L.A., Schotman, H., Jansen, M.-W., Riva, R., Sabadini, R. (2004) High-Harmonic Geoid Signatures due to Glacial Isostatic Adjustment, Subduction and Seismic Deformation. In: *GOCE, The Geoid and Oceanography, Proceedings of Second International GOCE user workshop*, ESA-ESRIN, Frascati, Italy, March 8-10, 2004.

**Tidal datum**

1. Gomis, D.,Tsimplis, M., Marcos, M., Fenoglio-Marc, L., Pérez, B., Raicich, F., & Monserrat, S. (2012). Mediterranean Sea level variability and trends. *The Climate of the Mediterranean Region*, 257-299.

2. Bert, R. (2018) The Urban Ocean: The Interaction of Cities with Water, by Alan F. Blumberg and Michael S. Bruno. New York City: Cambridge University Press, *Civil Engineering – ASCE*, *89*(2), 74-74.

3. Featherstone, W. E., & Filmer, M. S. (2012). The north-south tilt in the Australian Height Datum is explained by the ocean's mean dynamic topography. *Journal of Geophysical Research: Oceans*, *117*(C8).