Developing New National Geodetic Reference Frame of Nepal

Narayan Regmi[1], Sandesh Upadhyaya[1], Manisha Thapa[1], Shiva Prasad Lamsal[1] & Suraj Bahadur KC[1], Suresh Shrestha[1], Sushmita Timalsina[1], Dipesh Suwal[1], Mahesh Thapa[1], Shanker KC[1]
nregmi2000@gmail.com, sandeshupadhya1@gmail.com, ,thapamanisha2049@gmail.com, shivaplamsal@gmail.com, kcsuraj21@gmail.com, Shrestha.suress@gmail.com, qust04sharma@gmail.com, dipeshsuwal@gmail.com, mahesh100thapa@gmail.com, shankerkc01@gmail.com
[1]Survey Department

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ABSTRACT

Geodetic reference frame is fundamental geodetic infrastructure required for positioning for surveying and mapping purposes. This paper presents a method to develop national level geodetic reference frame tied to global reference frame by utilizing the long-term GNSS observations. The key to realize a national reference frame is to transform Earth-Centered Earth-Fixed (ECEF) X, Y, and Z coordinates from International Terrestrial Reference Frame (ITRF) to national reference frame is by application of 14-Helmert transformation parameters. Initially, precise point positioning (PPP) provides the X, Y, and Z coordinates of reference stations with respect to ITRF, which in turn transformed to national geodetic reference frame. This paper discusses the development of 14-Helmert transformation parameter taking example of Nepal geodetic reference frame being built in near future.

1 INTRODUCTION

Geodetic reference system and frame is fundamental requirements for positioning, navigation, monitoring geological hazards and many geoscientific studies. In surveying and mapping domain, positioning is done with respect to such fundamental reference frame. Topographical and cadastral mapping, engineering surveying and others rely on geodetic reference frame. In context of Nepal, SOI datum (Survey of India) was used for topographical mapping and cadastral mapping before 1986 (KC & Acharya, 2022). In 1986, a newer geodetic datum called Nepal Datum was built and has been used for surveying and mapping activities within Nepal. Thus, Nepal Datum is the current national geodetic datum in use by Survey Department (SD).

The earth is a dynamic system and positional coordinates of reference stations anchored / fixed at its crust is a function of time due to geophysical motion. However, Nepal Datum is static in nature thus positional coordinates of 68 higher-order control points remain static. The details of development of conventional topocentric geodetic datum can be found in (Bomford, 1962).

Nepal lies at the converging boundary of Indian and Eurasian tectonic plates and tectonic motion of these two plates cause the earth crust to displace. Such crustal motion is secular in nature. The displacement accumulates at constant rate. Over the long period, the accumulated displacement will be larger than the precision of positional coordinates referenced to conventional terrestrial datum (e.g. Nepal datum). In addition, the Gorkha earthquake of 2015 has displaced the central and eastern Nepal significantly in non systematic way. The horizontal displacement of more than 1.5m have been recorded in vicinity of Kathmadu (Shrestha, 2017). This has forced us to find the solution.

Modern geodesy is characterized by space geodetic technologies. Space geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Global Navigation Satellite System (GNSS) have enabled us to build geocentric terrestrial reference frames. These technologies have made 3D ECEF Cartesian coordinate system realization possible. Moreover, among these systems, GNSS offers ease of operation and economic, and capability to build geocentric reference frame at regional, national, and global level (Soler & Snay, 2004).

The power of GNSS to build a geocentric reference frame and its ability to collect continuous observations that can provide time-dependent variations of position due to geophysical motion. Such capability of GNSS is used to build the national geodetic reference frame. At regional and national level, it has been the standard practice to establish uniformly distributed continuously operating reference stations (CORS) forming region-wide or nationwide CORS network. Then, long-term GNSS observations obtained from such CORS stations are utilized to define and develop national geodetic reference frame with respect to global reference frame.

National geodetic reference frame is defined and developed tied to global reference frame by application of 14-parameter Helmert transformation. For example, the current realization of the North American Datum of 1983 (NAD83 (2011)) is defined in terms of 14-parameter transformation from ITRF08 (Pearson & Snay, 2013). Similarly, North American Reference Frame NA12 also implements daily 7-parameters from IGS08 (Blewitt et al., 2013). At present, such global reference frame is International Terrestrial Reference Frame (ITRF). International Earth Rotation and Reference System Services (IERS) is service of International Association of Geodesy (IAG), which is a responsible organization that define, develop, and maintain the ITRF. Recent ITRF version is ITRF2020. The main idea of this paper is to present the process of determining 14-parameters of Helmert transformation to convert ITRF positional coordinates of reference stations into national geodetic reference frame.

The significance of geodetic reference frame has been acknowledged worldwide, leading to the adoption of the UN General Assembly Resolution on the Global Geodetic Reference Frame for Sustainable Development. This resolution highlights the critical need for a globally coordinated approach to geodesy. Furthermore, the necessity of newer geodetic reference frame to improve upon the limitations of existing geodetic datum; adoption of best practices of surveying and mapping techniques followed and recommended internationally; and aim to improve the accuracy of surveying and mapping and help to resolve disputes related to land boundaries, are motivations to develop national geodetic reference frame.

The new geodetic reference frame, in addition to providing stable reference frame for geo-scientific studies, it is also expected to decrease time and cost of surveying and mapping activities. New geodetic reference frame being compatible with modern surveying technologies, brings quality and thus trust in surveying and mapping works.

In this paper, the first section introduces the necessity of 3D ECEF reference frame. The second section presents the high-precision GNSS positioning focused to develop reference frame. The third section, the key section of this paper presents the mathematical aspect of realization of national geodetic reference frame taking example Nepal reference frame in coming years. Final section concludes this paper.

2 GNSS POSITIONING

Two approaches of high-precision GNSS positioning exists: 1) relative positioning, and 2) absolute positioning. Relative positioning approach implements double-differencing (DD) method to derive precise position. In this approach, two or more GNSS stations/ receivers / units simultaneously make the observations. One of the station is fixed station / acts a reference /base station. The position of other /remaining GNSS stations (rover stations) is determined relative to reference stations. As reference and rover stations are closely spaced, both share identical atmospheric condition and same satellite errors, thus common errors and biases are removed in DD method, resulting highly precise relative position (Odijk & Wanninger, 2017). Absolute positioning implements precise point positioning (PPP) method, which uses un-differenced, dual frequency, pseudorange and carrier-phase observations along with precise satellite orbit and clock products, and corrections for various effects, for standalone static point positioning at millimeter level precision (Kouba et al., 2017; Zumberge et al., 1997). Compared to differential positioning approach, PPP doesn't require simultaneous observations, which is the single most, greatest advantage that PPP offers. In addition, as globally consistent satellite orbits and clocks are used in PPP processing, the consistent position of all GNSS stations worldwide or within the country in our case, are obtained in global reference frame, such as ITRF (e.g. ITRF2020). In our purpose here, to develop a national reference frame from stations in CORS network, we consider PPP method to derive positions.

The set of homogeneous coordinates and velocities is determined by using GNSS observations collected at CORS stations using daily/weekly station position estimates and velocity estimates, long term position time series, discontinuities as well as post-seismic and co-seismic offsets. The use of long-term position time series enables a more accurate geophysical analysis of the observed site movement, particularly in understanding residual signals or non-linear motion that is linked to local geophysical events or site stability (Dawson et. al, 2009).

3 REALIZATION OF NATIONAL GEODETIC REFERENCE FRAME 2025 (NEP25)

Defining a terrestrial reference frame means defining / fixing the origin, orientation, scale and rate of change of these parameters over time. This terrestrial reference frame is 3D Earth- ECEF – XYZ Cartesian coordinate system. IERS has taken the responsibility of defining and developing the standards of International Terrestrial Reference System (ITRS) and its physical-mathematical realization International Terrestrial Reference Frame (ITRF) (Petit and Luzum, 2010). ITRF is such 3D ECEF-XYZ coordinate system. The positional coordinates of any point on or above the surface of the Earth are described by X, Y, and Z triplets. ITRFs are updated in regular interval reflecting the dynamics of Earth system and thus positional coordinates as the function of time. A recent release of ITRF is ITRF2020, the previous being ITRF2014. These ITRFs are developed utilizing long-term space geodetic observations worldwide.

While ITRF is global reference frame (e.g. ITRF2020), national scale reference frame (e.g. NAD83 (2011)) and regional scale reference frame (e.g. NChina16) are required to cater the needs of national or regional scale requirements such as national geodetic reference frame for surveying and mapping, crustal motion studies or geological hazards monitoring. Geodetic reference frame for surveying and mapping is fundamental infrastructure of any nation or region. Within the scope of this paper, we name such national geodetic reference frame, going to be built in near future by Geodetic Survey Division (GSD) a Nepal Reference Frame 2025 (NEP25).

In context of developing regional reference frame, long-term GNSS observations of more than 3 years from reference stations (CORS stations that qualify to be reference stations) are utilized (Wang et al., 2013). For examples, a regional reference frame of Gulf of Mexico has been developed using continuous observation of 13.5 years on average (Wang et al., 2020). Similar kind of regional reference frame of Caribbean region exists using observations of greater than 3 years period (Wang et al., 2019). Observations of more than 5 years have been used to develop reference frame of Houston, Texas (Kearns et al., 2019). Reference stations have the characteristics of 1) having good geographical distribution, 2) having long-term observations, 3) consistent daily position time series, and 4) located in stable site (Wang et al., 2013). In coming years, NEP25 is going to be developed from GNSS observations of more than 3 years period from about 30 CORS stations, being established in coming years by GSD.

A national geodetic reference frame is often developed through a simultaneous transformation from global terrestrial reference frame (Pearson & Snay, 2013; Soler & Snay, 2004; Wang et al., 2013, 2018, 2020). For example, the current realization of the North American Datum of 1983 (NAD83 (2011)) is defined in terms of 14-parameter transformation from ITRF08 (Pearson & Snay, 2013). Similarly, North American Reference Frame NA12 also implements daily 7-parameters from IGS08 (Blewitt et al., 2013). NEP25 is going to be defined in terms of 14-parameter Helmert transformation from recently released ITRF2020. The PPP processing delivered ITRF2020 based positional coordinates are transformed to NEP25 positional coordinates by application of 14-parameter Helmert transformation (Soler & Snay, 2004; Wang et al., 2013). Helmert transformation produces distortion-free transformation of the ECEF-XYZ coordinates between two reference frames. This method transforms a set of points from one reference frame into another by translation, rotation, and scaling.

Let $x(t)_{NEP25}$, $y(t)_{NEP25}$ and $z(t)_{NEP25}$ denote the NEP25 positional coordinates for a point at any epoch *(t)* as expressed in a 3D ECEF cartesian coordinate system. These coordinates are expressed as a function of time to reflect the reality of the crustal motion associated with plate tectonics, land subsidence, volcanic activity, postglacial rebound and so on (Soler & Snay, 2004). Similarly, let $x(t)_{ITRF}$, $y(t)_{ITRF}$ and $z(t)_{ITRF}$ denote ITRF2020 positional coordinates for this same point at same epoch *(t)*. Then, ITRF2020 coordinates are related to their corresponding NEP25 coordinates by a Helmert transformation that is approximated by the following equations:

$$\begin{bmatrix} x(t)_{NEP25} \\ y(t)_{NEP25} \\ z(t)_{NEP25} \end{bmatrix} = \begin{bmatrix} T_x(t) \\ T_y(t) \\ T_y(t) \end{bmatrix} + \left(1 + s(t)\right) \begin{bmatrix} 1 & \omega_z(t) & -\omega_y(t) \\ -\omega_z(t) & 1 & \omega_x(t) \\ \omega_y(t) & -\omega_x(t) & 1 \end{bmatrix} \times \begin{bmatrix} x(t)_{ITRF} \\ y(t)_{ITRF} \\ z(t)_{ITRF} \end{bmatrix} \quad (1)$$

Here $T_x(t)$, $T_y(t)$, and $T_z(t)$ are translations along the X, Y, and Z axes, respectively; $w_x(t)$, $w_y(t)$ and $w_z(t)$ are counterclockwise rotations about these same three axes; and *s(t)* is differential scale change between ITRF2020 and NEP25. These approximate equations suffice because the three rotations usually have rather small magnitudes. The differential scale change *s(t)* can be set to zero, hence the scale factor to be unity (Soler & Snay, 2004). The function of scale factor and its value should be such that it enforces minimum distortion of point-to-point distances between reference frames. Studies have shown that the scale factor of unity have negligible effect for coordinate transformations from a global reference frame to a regional reference frame (Wang et al., 2013). Therefore, the coordinate transformation from ITRF2020 to NEP25, with unity scale factor, can be written as (from (Wang et al., 2013)):

$$\begin{aligned} x(t)_{NEP25} &= T_x(t) + x(t)_{ITRF} + \omega_z(t) \,.\, y(t)_{ITRF} - \omega_y(t) \,.\, z(t)_{ITRF} \\ y(t)_{NEP25} &= T_y(t) - \omega_z(t).x(t)_{ITRF} + y(t)_{ITRF} + \omega_x(t) \,.\, z(t)_{ITRF} \\ z(t)_{NEP25} &= T_z(t) + \omega_y(t).x(t)_{ITRF} - \omega_x(t) \,.\, y(t)_{ITRF} + z(t)_{ITRF} \end{aligned} \tag{2}$$

where, $T_x(t), T_y(t), T_z(t), w_x(t), w_y(t)$, and $w_z(t)$ are the six Helmert transformation parameters at epoch *(t)*.These parameters at a specific epoch can be calculated using positional coordinates of reference stations in both ITRF2020 and NEP25 frame.

Positional coordinates of reference stations in both frames: ITRF2020 and NEP25 at a specific epoch, can be utilized to calculate these six transformation parameters at that epoch. Two common points in both frame will provide a set of linear equations with six equations and with six unknowns. Thus unique solution of six unknowns (three translation and three rotation parameters) can be solved. However, we will have more than 30 reference stations, allowing us to use least squares method to obtain better transformation parameters, resulting better transformation from ITRF2020 to NEP25 (Wang et al., 2018). It is worth noting that NEP25 is ECEF terrestrial reference frame designed and developed to cover territory of Nepal. At certain arbitrary epoch, NEP25, national geodetic reference frame is aligned with ITRF2020. At this epoch, because both are aligned with each other, their origin, scale and axes are same. Within the scope of this paper, we chose such epoch to be *(t_0 =2025.0)*. Therefore, at this epoch about 30 reference stations will have the same XYZ coordinates with respect to both reference frame, as expressed in following equations:

$$\begin{aligned} x_{NEP25}(2025.0) &= x_{ITRF}(2025.0) \\ y_{NEP25}(2025.0) &= y_{ITRF}(2025.0) \\ z_{NEP25}(2025.0) &= z_{ITRF}(2025.0) \end{aligned} \tag{3}$$

Theoretically, a reference site should be ideally stable with respect to regional reference frame (a velocity of frame station should be minimized to zero with respect to NEP25), which means the coordinates of frame stations remain almost similar at different epochs with respect to national reference frame. Therefore, for any other epoch, let's say *(t=2028.0)* following expression holds:

$$\begin{aligned} x_{NEP25}(2028.0) &\approx x_{NEP25}(2025.0) \\ y_{NEP25}(2028.0) &\approx y_{NEP25}(2025.0) \\ z_{NEP25}(2028.0) &\approx z_{NEP25}(2025.0) \end{aligned} \tag{4}$$

For the epoch *(t = 2028.0)*, coordinates of reference stations in NEP25 can be obtained using equation (4) and (3). For the same epoch *(t = 2028.0)*, coordinates of the same reference stations in ITRF2020 is obtained by PPP processing. Thus, as coordinates of about 30 common reference stations in both frames are available, the six parameters: *(T_x, T_y, T_z, w_x, w_y, and w_z)* to transform from ITRF2020 to NEP25 at epoch *(t = 2028.0)* can be estimated from equation (2) by using least squares method to solve the inverse equation.

These six parameters are also a function of time and shows a linear relationship with time (Soler & Snay, 2004). This linear relationship can be expressed by following equations:

$$\begin{aligned} T_x(t) &= T_x(t_0) + \dot{T}_x \,.\, (t - t_0) \\ T_y(t) &= T_y(t_0) + \dot{T}_y \,.\, (t - t_0) \\ T_z(t) &= T_z(t_0) + \dot{T}_z \,.\, (t - t_0) \\ \omega_x(t) &= \left[\epsilon_x(t_0) + \dot{\epsilon}_x \,.\, (\dot{t} - t_0)\right].m_r \\ \omega_y(t) &= \left[\epsilon_y(t_0) + \dot{\epsilon}_y \,.\, (\dot{t} - t_0)\right].m_r \\ \omega_z(t) &= \left[\epsilon_z(t_0) + \dot{\epsilon}_z \,.\, (\dot{t} - t_0)\right].m_r \\ s(t) &= s(t_0) + \dot{s} \,.\, (t - t_0) \end{aligned} \tag{5}$$

where $(m_r = 4.84813681 \times 10^{-9}$ is conversion factor from milliarcseconds (mas) to radians. Here, (t_0) denotes a fixed time commonly called the reference epoch date (*e.g.* $(t_0 = 2025.0)$). Hence the seven quantities $(T_x, (t_0), T_y (t_0), T_z (t_0), w_x (t_0), w_y (t_0)\ wz(t_0)$, *and* $s(t_0)$ are all constants. The seven other quantities, $T_x, T_y, T_z, w_x, w_y, w_z$, *and* $\dot{s}$ which represents rates of change with respect to time, are also assumed to be constants.

It can be seen in above equation (5) that six parameters at any epoch can be determined. are six Helmert transformation parameters at epoch ($t_0 = 2025.0)$ and equals zero as NEP25 is aligned to ITRF2020. Taking ($t_0 = 2025.0)$ and ($t = 2028.0)$, one can determine the rate of change of these six parameters using equation (5). Rearranging equation (5) and substituting ($t_0 = 2025.0$ *and* $t=2028.0)$, we have following expression rearranged from (Wang et al., 2013) :

$$\dot{T_x} = \frac{T_x(2028.0) - T_x(2025.0)}{(2028.0 - 2025.0)}$$
$$\dot{\omega_x} = \frac{\omega_x(2028.0) - \omega_x(2025.0)}{(2028.0 - 2025.0)} \quad (6)$$

The first expression in equation (6) can be used to determine rate of 3 translation parameters, and second expression can be used to determine the rate of 3 rotation parameters. Equation (6) provides the rate of six parameters required by equation (5).

Combining equation (2) and equation (5), the XYZ positional coordinates of a point / reference stations stations at any epoch *(t)*, with respect to NEP25 can be obtained using the following equations:

$$\begin{aligned} x(t)_{NEP25} &= \dot{T}_x.(t-t_0) + x(t)_{ITRF} + \dot{\omega}_z.(t-t_0).\ y(t)_{ITRF} - \dot{\omega}_y.(t-t_0).\ z(t)_{ITRF} \\ y(t)_{NEP25} &= \dot{T}_y.(t-t_0) - \dot{\omega}_z.(t-t_0).x(t)_{ITRF} + y(t)_{ITRF} + \dot{\omega}_x.(t-t_0).\ z(t)_{ITRF} \\ z(t)_{NEP25} &= \dot{T}_z.(t-t_0) + \dot{\omega}_y.(t-t_0).x(t)_{ITRF} - \dot{\omega}_x.(t-t_0).y(t)_{ITRF} + z(t)_{ITRF} \end{aligned} \quad (7)$$

$x(t)_{ITRF}, y(t)_{ITRF}$, *and* $z(t)_{ITRF}$ are positional coordinates with respect to ITRF2020, which can be obtained by PPP processing. ($\dot{T}_x, \dot{T}_y, \dot{T}_z, \dot{w}_x, \dot{w}_y, \dot{w}_z$) can be obtained from equation (6). Thus, the coordinate transformation of the GNSS-derived positional time series from ITRF2020 to NEP25 can be accomplished by a set of seven parameters: the epoch aligning two reference frames (t_0), and rate of change of three translations and three rotations ($\dot{T}_x, \dot{T}_y, \dot{T}_z, \dot{w}_x, \dot{w}_y, \dot{w}_z$)

4 DISCUSSION

GSD is planning to establish about 30 CORS stations nationwide with the objective of defining national geodetic reference frame. Till the time of preparation of this manuscript, site selection work has been accomplished and construction of monument of these CORS station is ongoing. In future, when these CORS stations in operation and collect long-term observations, such long-term observations are utilized to define national geodetic reference frame. Such geodetic reference frame such as NEP25, can be defined / developed in terms of ITRF (e.g. current release ITRF2020) by application of 7- Helmert transformation parameters as explained in section 3. In future, NEP25 will be made accessible in forms of positional coordinates of about 30 reference stations at reference epoch, in our case ($t_0 = 2025.0)$ and rates of six parameters: ($\dot{T}_x, \dot{T}_y, \dot{T}_z, \dot{w}_x, \dot{w}_y, \dot{w}_z$). Initially, user gets the positional coordinates of his/her site with respect to ITRF2020 obtained after PPP processing. Then he/she will apply transformation from ITRF2020 to NEP25 to get positional coordinates with respect to NEP25.

To better estimate rates of six parameters, GNSS observation of longer period, minimal of 3 years are required as shown by various studies (Wang et al., 2018) in order to deliver the millimeter level precision in position. National geodetic reference frame should be updated at regular interval of years: 1) as longer period of observations will be available in future, 2) as newer release of ITRF will occur in future. In future, more / additional reference stations with longer period of observations would be beneficial such that better estimated site velocity will be obtained improving the stability of the reference frame.

5 CONCLUSIONS

With the aim of developing a national geodetic reference frame for Nepal, establishment of CORS network across the country has been initiated by GSD, SD. In this context, this paper provides an overview for the analysis and strategy to be adopted for realization of national geodetic reference frame utilizing long-term observations from nationwide established CORS stations.

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Author's Information

Name	:	Narayan Regmi
Academic Qualification	:	Masters in Geoinformation Management
Organization	:	Geodetic Survey Division, Survey Department
Current Designation	:	Deputy Director General
Work Experience	:	30 years
Published paper/article	:	1