DrukRef21 – defining the reference frame of Bhutan in a deforming region

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SUMMARY

Bhutan was one of the first countries in Asia implementing a new geocentric national reference frame based on the modern space-geodetic techniques, namely GNSS (Global Navigation Satellite Systems). DrukRef03 was implemented by observing five points of the classical 0-Order network in campaign mode that was linked to ITRF2000 at the epoch 2003.87.
In the earlier twenty-tens, a network of six Permanent GNSS Reference Stations (PRS) was installed covering the south and central part of Bhutan. This network, DrukNet, was aligned with DrukRef03 through dedicated observation campaigns of the classical network.
Bhutan is located in the deforming region of the tectonic plate boundary between the Indian and Eurasian tectonic plates. The continuous tectonic processes created by the collision of the Indian plate against the Eurasian plate has formed the Himalayan Mountain range that continues to be built up presently. Such internal deformations have been accurately estimated using the PRS observations and are reaching 0.6 cm/yr between the south and central part of Bhutan. This implies an internal deformation of the DrukRef03 reference frame of more than 10 cm since its creation.
Additionally, the use of a network of PRS stations to materialize permanently the national frame is more accurate than its definition using episodic stations. The recent densification of the DrukNet with three more stations also require the estimation of coordinates to these stations with respect to the national reference frame.
Therefore, it was decided to implement a new reference frame, called DrukRef2021, that is continuously materialized by the PRS. Although DrukRef2021 is a static datum, i.e., with coordinates referred to the reference epoch (2021.8), a velocity field covering Bhutan has been also estimated that will mitigate the internal deformations caused by the tectonic processes and permit that DrukRef2021 will be used for a long period.

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1. INTRODUCTION

1.1 DrukRef03

The National Land Commission Secretariat (NLCS) is the responsible governmental agency for the definition and maintenance of the national reference of Bhutan. NLCS has promoted the implementation of one of the first geocentric reference frames in Asia back in 2003 when DrukRef03 was defined through the observation of six points of the classical 0-Order network in campaign mode that was linked to ITRF2000 at the epoch 2003.87 (Jivall, 2003). Additionally, the coordinates of 38 points of the 1st order geodetic network of Bhutan where also computed (Lilje, 2004) to materialize DrukRef03 for most of the territory of Bhutan.

DrukRef03 was firmly adapted by NLCS as the national reference frame of Bhutan being in use since. All geo-referencing activities have been official conducted with respect to DrukRef03 in the last decades.

Concerning the vertical component, NLCS also promoted the modernization of the reference frame with the adoption of DrukGeoid2015 (Fernandes and Bos, 2015), a geoid based on EIGEN-6C (Förste et al., 2011), enhanced by local gravimetric observations. DrukGeoid2015 permits to have full consistent positions in all 3D spatial components.

1.2 DrukNet – Permanent Reference Network of Bhutan

DrukNet, the Permanent Reference Network of Bhutan, was created in 2011/2012 with the installation of six stations distributed by the entire territory of Bhutan. In recent years, there was an effort to rehabilitate and densify the network by adding two new stations and incorporate two others existing PRS stations in DrukNet. There are also plans to further densify the network in the coming years to complete the coverage of much of the inhabited territory of Bhutan with a network capable of providing RTK corrections.

Figure 1 shows the distribution of the DrukNet network that is presently formed by nine stations since DEOT has been recently decommissioned.

The PRS stations permit to guarantee continuously the quality of all reference points by monitoring their behaviour (which is not possible at geodetic markers which can be destroyed, vandalized, moved) and to optimize resources since the PRS sites are mainly used as reference for local geo-referencing activities, namely by streaming RTK corrections or be used as reference for post-processing. Figure 2 shows the time-series of daily positions for THIM (Thimphu) since its installation, which analysis permit to evaluate the stability of the stations or any change on the positions (like in 2020 due to an antenna change).

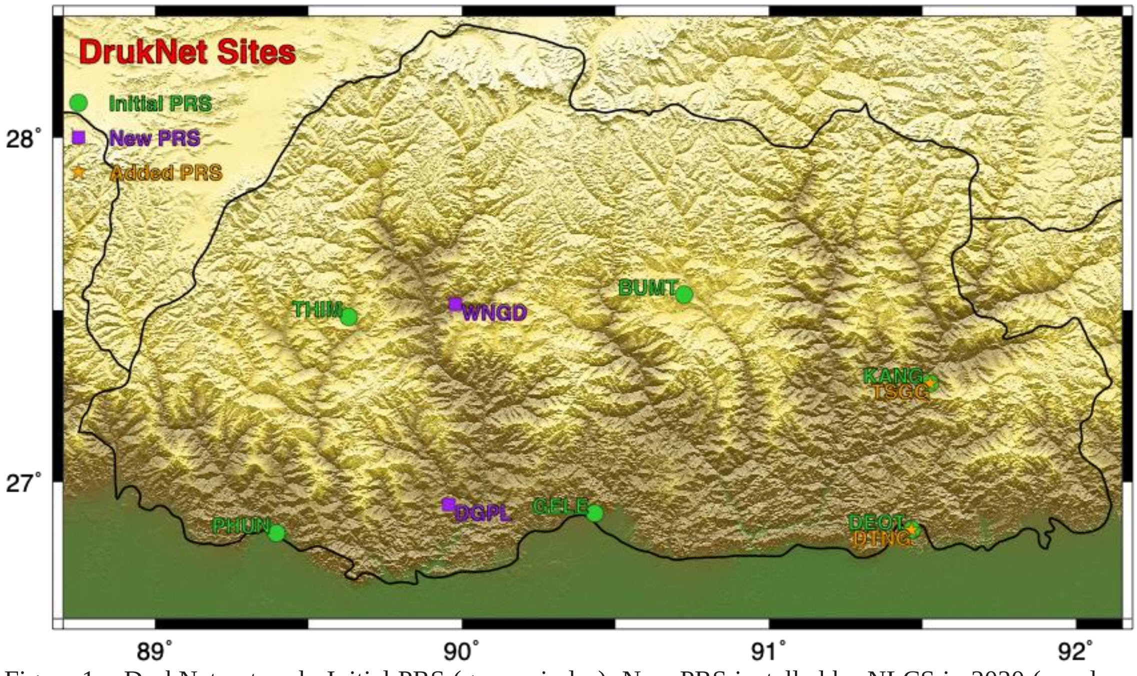

Figure 1 – DrukNet network: Initial PRS (green circles); New PRS installed by NLCS in 2020 (purple squares); existing PRS added to the network (orange stars)

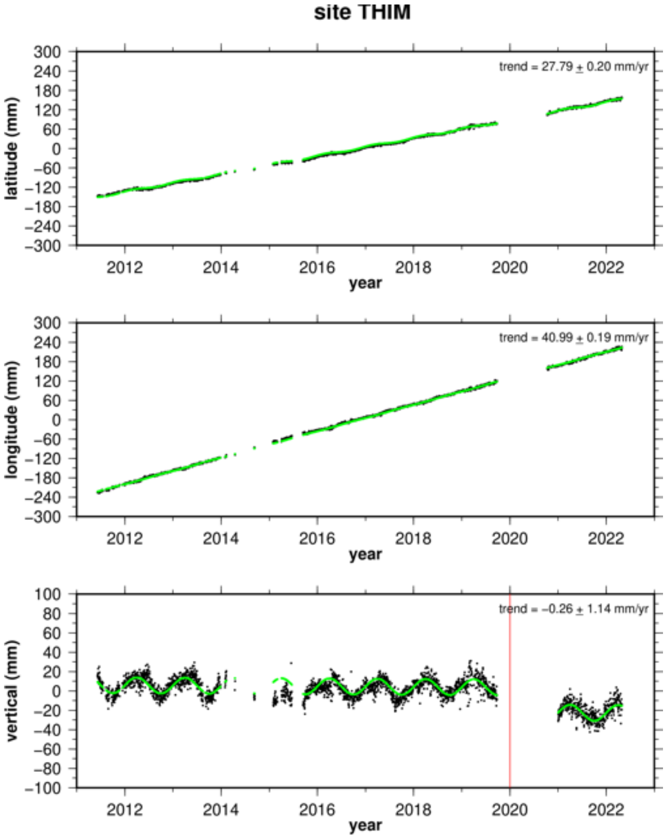

Figure 2 – Time-series of daily positions (black points) for the THIM (Thimpu) PRS station and derived velocity showing also seasonal variations (green line).

1.3 Tectonic settings of Bhutan – Velocity Field

Bhutan is situated in the Himalayas. This mountain range has been created as the result of the collision between Indian and Eurasian plates (around 45-65 Ma) and associated crustal shortening (Rowley, 1996). These processes continue to be active on the present-day (Rajendran and Rajendran, 2022) leading an internal crustal deformation mainly on the North-South direction as can be observed in Figure 3, which shows the horizontal velocities with respect to the India plate for the six stations installed in 2011/2012 (the data span for the stations installed in 2020 are still too short to derive reliable motions). It is clearly observed that the three stations in the southern part of the country has minor residual motions with respect to India then the central stations (if these stations were located in the India plate, the residuals will be negligible).

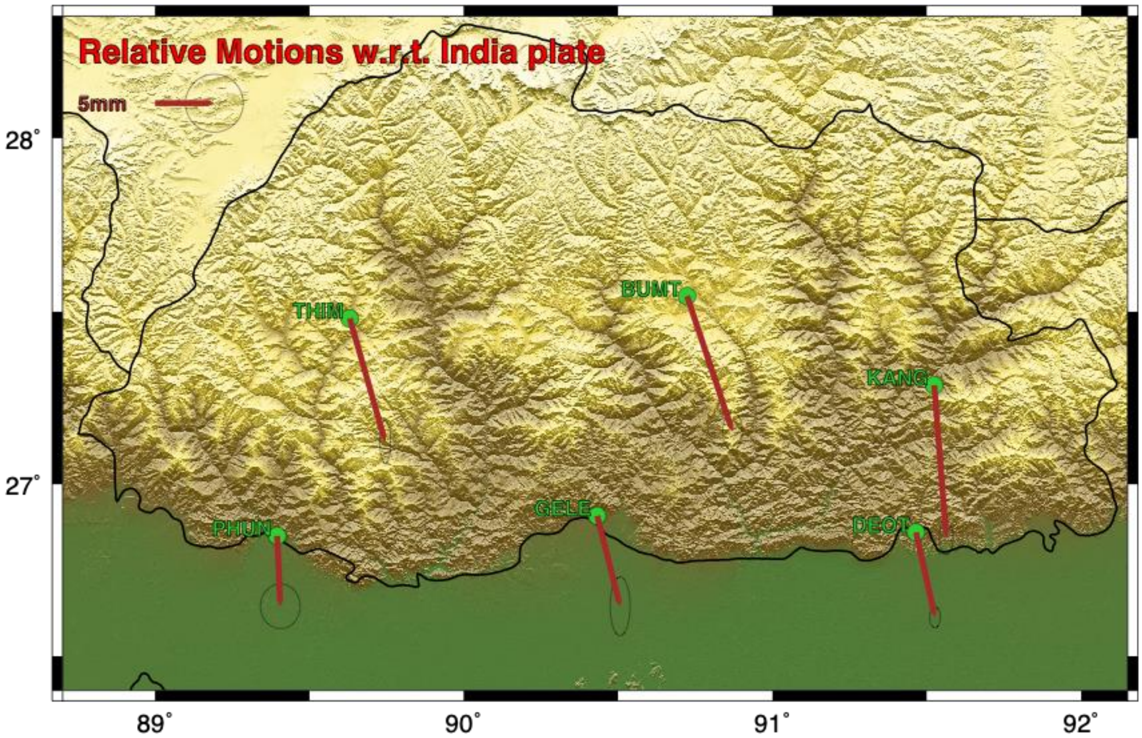

Figure 3 – Relative motions of the six older PRS stations with respect to Indian Plate.

Using the estimated velocities shown in Figure 3, it is possible to quantify that the internal shortening of the baselines between the average parallel defined by THIM, BUMT and KANG, and the average parallel defined by PHUN, GELE and DEOT, is about 5mm/yr. This implies that since 2003, when DrukRef03 was defined, the total shortening of the baselines between stations in the southern part of the country and stations in the central part is already about 9-10cm, which is very significative and could not been ignored when different PRS are used as reference for georeferencing applications.

1.4 DrukRef2021

NLCS have carried out several attempts to connect the PRS stations to DrukRef03 after their initial installation. However, due to their reliability and also the difficulty to update procedures, only individual connections were carried out and the PRS were never properly connected to DrukRef03. Furthermore, the report prepared by Fernandes (2018) showed the need to create a new reference frame based on the network of existing PRS in order to accommodate the internal deformations discussed in the previous section, and to follow the best world practices where currently the national reference frames are permanently materialized by PRS networks.
NLCS has participated in the 2019 campaign that occurred in the Pacific-Asia region to uniformize the reference frames in these regions (Hu, 2020), where the six existing stations and three 0-order stations were simultaneously observed. The initial plan was to use these 9 stations to define the new reference frame.
However, as already mentioned, during 2020 two new PRS stations were installed by NLCS and two another existing PRS stations were added to the DrukNet network (cf. Figure 1). In addition, only three points (0-order) with known coordinates in the old reference system (DrukRef03) had been observed in 2019. This limited number prohibited the computation of any transformation parameters between the DrukRef03 and the new reference frame even if to obtain a robust set of transformation parameters between DrukRef03 and any new reference frame was extremely difficult as demonstrated by Fernandes (2018) that clearly showed errors of several centimeters, particularly on the eastern part of Bhutan, caused by the internal deformation due to plate tectonics, possible local movements (e.g., earthquakes displacements), heterogeneous distribution of the classical network, and eventual errors on observations.
Finally, a new realization of the ITRS (International Terrestrial Reference System) called ITRF2020 (International Terrestrial Reference Frame, realization 2020) was programmed to be released during 2021 to replace ITRF2014 (realization 2014).
Consequently, it was decided to carry out a new campaign in 2021 where all PRS stations were simultaneously observed together with more 0– and 1–order passive geodetic markers that could create a homogenous reference frame linked to the latest global reference frame, and that could permit to estimate a set of transformation parameters to convert all existing geoinformation from DrukRef03 into the new DrukRef2021.

2 ESTIMATION OF DRUKREF2021

2.1 Field Work

Figure 4 shows the points observed in each campaign together with the PRS: PARO was the only passive geodetic marker observed in 2019 and 2021, and DEOT was only observed in 2019 (since it has been decommissioned in 2020). It is important to note that the two existing PRS that have been added to the DrukNet network (TSGG and DTNG) were not observed during these two campaigns because they were not operational. Consequently, two additional solutions were estimated using all available PRS, one in February 2021 and one in January 2022, to compute the coordinates for TSGG and DTNG, respectively.

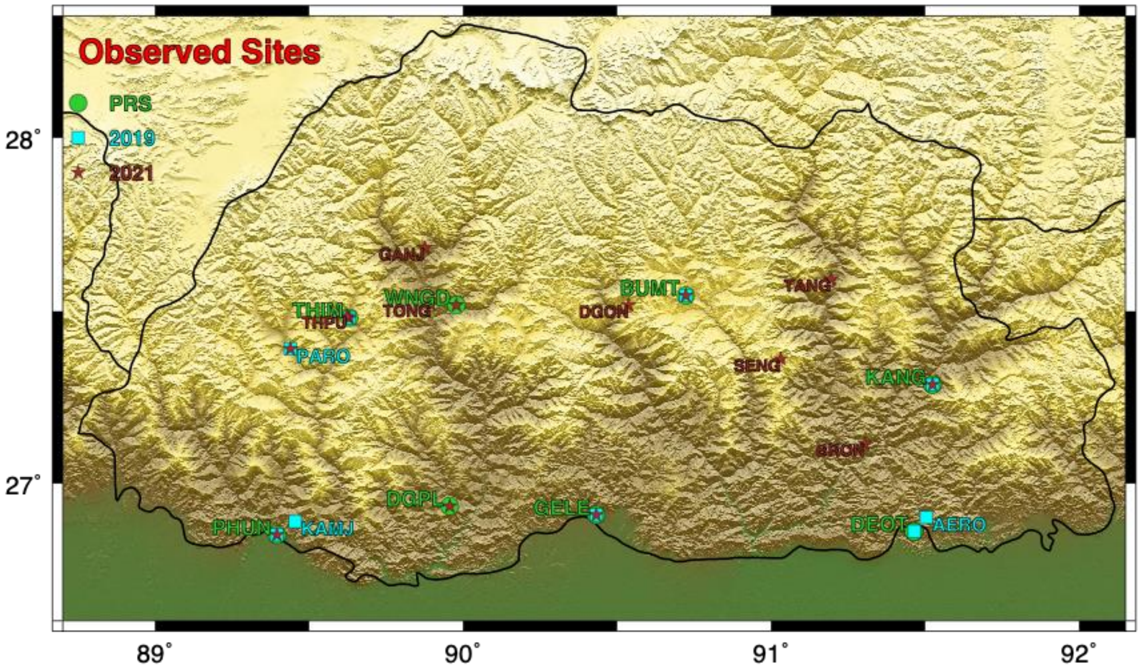

Figure 4 – Observed Sites: PRS (green circles); observed in 2019 (cyan squares); observed in 2021 (observed in 2021)

Table 1 summarizes the campaigns carried out to compute DrukRef2021 (the new datum for Bhutan, materialized through DrukNet) and also to estimate the transformation parameters between DrukRef03 and this new datum.

Table 1 – Statistics of the campaigns and solutions estimated to materialize DrukRef2021 and the transformation parameters between DrukRef03 and DrukRef2021

Campaign	Dates	Reference Epoch	PRS Stations	Passive Markers
2019	15-09-2019 – 21-09-2019	17-09-2019	6	3
2021	10-10-2021 – 30-10-2021	19-10-2021	7	7
2021 – TSGG	01-02-2021 – 15-02-2021	07-02-2021	5+1 (TSGG)	-
2022 – DTNG	01-01-2022 – 15-01-2022	07-01-2022	7+1 (DTNG)	-

Each passive marker was observed during the seven days of the 2019 campaign and a minimum of three days during the 2021 campaign. All available data for the PRS have been used for the estimation of the final coordinates in DrukRef2019.

2.2 Adopted Methodology

The normal procedure to materialize a national datum with respect to the latest realization of ITRS (e.g., ITRF2020) through a network of PRS is by selecting a period of several days (1-2 weeks) where all network stations have been observed. The positions of these stations are estimated with respect to the ITRFxxxx for each day with the best position computed by

performing a weighted average (with outlier removal) of the daily positions for the selected period. Any displacements (few tenths of millimeters) due to tectonic motions can be neglected and normally the reference epoch is selected to be the middle of the observation period.
However, in case of the estimation of DrukRef2021, some intermediate steps needed to be adopted because it was not possible to observe all PRS (and the passive geodetic markers) simultaneously in a single campaign.
Consequently, the solutions for each campaign (cf. Table 1) were first computed separately. Section 2.3 describes the methodology used to compute the individual solutions of each campaign in ITRF2014, the global reference frame adopted to perform the computations.
The 2021 campaign was selected as reference – consequently, the reference epoch for DrukRef2021 is 19th October 2021. Therefore, the next step was to transform the other individual campaign solutions (2019, 2021-TSGG, and 2022-DTNG) into the 2021 campaign, which is described in Section 2.4.
Finally, the coordinates of all stations (PRS and passive geodetic markers) were estimated with respect to ITRF2020 by applying the transformation parameters between ITRF2014 and ITRF2020 (ITRF2014toITRF2020, 2022).

2.3 Estimation of each campaign solution

The daily solutions of the positions of the permanent GNSS stations were computed with the GipsyX software package using the PPP - Precise Point Positioning strategy. The most recent version of this software was used (Bertinger et al., 2020). PPP is very efficient from a computational point-of-view (the required computational resources grows linearly with the number of stations) and it provides similar quality as other software packages (e.g., GAMIT or BERNESE) and approaches (e.g., double differencing).
The mapping into ITRF2014 of the daily solutions was carried out by estimating a seven-parameter Helmert transformation using several dozens of IGS (International GNSS Service) stations globally distributed as reference. The core of this reference network is the set of IGS14 stations.
The unique solution for all PRS stations, computed using as reference epoch the middle of the campaign of observations was estimated by performing a weighted average of the daily solutions, using dedicated scripts developed at University of Beira Interior (Portugal). 2019 and 2021 show slight worse statistics due to the less quality of the observations at the passive markers, which are many times not adapted to being observed with GNSS equipment.

Table 2 – Statistics of the campaigns (r.m.s. of the residuals per coordinate, number of stations, number of days – between parenthesis the number of station / days observed at each observed passive marker)

Campaign	E (mm)	N (mm)	U (mm)	# Stations	# Days
2019	1.7	2.5	8.3	9 (3)	7 (7)
2021	2.2	2.8	13.8	15 (8)	21 (3)
2021 – TSGG	1.4	1.2	4.6	6 (0)	15 (0)
2022 – DTNG	1.2	1.3	4.2	8 (0)	15 (0)

2.4 Combination in a single solution

The next step to obtain the final coordinates of the PRS (and observed passive geodetic markers) with respect to ITRF2014 was to combine the four independent campaigns: 2019, 2021-TSGG, 2022-DTNG, and 2021. The last one was used as reference and three different transformation parameters (7 Helmert transformation) were computed from the 2019, 2021-TSGG and 2022-DTNG campaigns into the 2021 campaign.

It was performed three sequential combinations using the transformed coordinates, now referred to the 2021 reference epoch, starting with the 2019 campaign. This generated a new set of unique coordinates that was combined with the transformed coordinates of the 2021-TSGG campaign. Finally, the same procedure was once again repeated with the coordinates of 2022-DTNG in order to obtain the final coordinates.

Please notice that with this procedure the final coordinates are a combined average of the campaign solutions after all of them have been aligned with respect to ITRF2014 at the reference epoch of October 19th, 2021.

Table 3 shows the main statistics for the transformation. It is observed that the transformation from 2019 into 2021 has large residuals, particularly in the vertical component. The most probable reason is the change of antenna in two of the stations in 2020 that caused a slight change in the coordinates. This also demonstrates that should be avoided to change antennas unless that strictly necessary.

Table 3 – Statistics of the transformation parameters between each individual campaign and the reference one – 2021 (r.m.s. of the residuals per coordinate, number of common points)

Campaign	E (mm)	N (mm)	U (mm)	# Stations
2019	5.3	8.9	24.3	5
2021 – TSGG	1.9	4.0	3.0	4
2022 – DTNG	1.1	0.9	3.1	7

3 CONCLUSIONS

DrukRef2021, the new datum of Bhutan, is now permanently materialized by the DrukNet network in a total of nine stations since DEOT was decommissioned in 2021 even if the coordinates for this station have been also estimated.

The nine PRS stations are directly managed by NLCS, which permit to have full and permanent control on the coordinates realizing the reference frame. This is also carried out through MIRAnet (https://miranet.druknet.net), the software that permits to manage the data and the users accessing DrukNet. Any failure on data dissemination is rapidly detected. In addition, MIRASpaco updates every month the time-series of the positions of all DrukNet stations to identify any abnormal displacement that can imply that the reference coordinates of the PRS station will need to be corrected.

The velocity field estimated for the PRS stations (cf. Figure 3) is also being used to estimate a gridded file that will be applied to convert points observed at any given epoch into the Reference Epoch of DrukRef2021 – 19th October 2021. The application of this grid is being under investigation before being formally adopted.

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