



DrukRef23

National Reference Frame of Bhutan

DrukGeoid22

Summary Report

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Executive Summary

Bhutan’s national geoid, DRUKGEOID15, was introduced in 2015 to replace global models such as EGM2008 and EIGEN-6C4. It was computed from 255 points where both GNSS positions and gravity were measured by the National Land Commission Secretariat (NLCS), covering the country from 88.5°E to 92.5°E in longitude and 26.5°N to 28.5°N in latitude with 0.02° resolution, and was constrained to the benchmark TH01 (located at the NLCS headquarters) so that the GNSS ellipsoidal height minus the geoid undulation matched the official orthometric height at that point. The model used a remove-restore procedure with the EIGEN-6C4 geopotential model and SRTM topography; comparisons with GNSS/levelling benchmarks showed a standard deviation of about 0.55 m.

DRUKGEOID22 is a 2022 update that applies a constant vertical offset of 0.8761 m to DRUKGEOID15 because the original fundamental benchmark TH01 was destroyed and replaced by the more reliable zero-order station THIZ. The updated grid retains the same spatial coverage and resolution as DRUKGEOID15 and includes the bias directly, so users need not apply any additional adjustment when using the DRUKGEOID22 files. The model is used to convert GNSS-derived ellipsoidal heights to orthometric heights within Bhutan’s vertical datum; it is defined with respect to the GRS80 ellipsoid and can therefore be applied to coordinates expressed in DRUKREF23 (which is an ITRF realisation using the same ellipsoid), provided that the geoid undulation from DRUKGEOID22 is subtracted from the ellipsoidal height.

1 Methodology

1.1 Data Acquisition

The foundation of the DRUKGEOID model is a national campaign of gravity and GNSS observations. Two SCINTREX CG-5 gravimeters were used to measure gravity at 271 sites across Bhutan between November 2014 and May 2015. Of these, 255 stations yielded both gravity and GNSS data. Multiple re-occupations at selected points helped monitor instrument drift. Gravity measurements were corrected for solid-Earth tides and instrument drift; readings taken when instrument temperature differed from nominal by more than 0.02 K or when the sensor tilt exceeded 50 arc seconds were discarded to ensure quality. Early battery issues, which initially produced a network standard

deviation of ~ 0.7 mGal, were resolved by mid-campaign, reducing the standard deviation to ~ 0.3 mGal.

Ellipsoidal positions and heights at each gravity station were determined using geodetic-grade GNSS receivers. Observation sessions averaged around one hour. Where permanent reference stations were within about 50 km, differential GNSS processing was performed; otherwise, Precise Point Positioning services were used. Vertical offsets between antenna and gravimeter were measured at each site, and multiple GNSS solutions were combined by weighted averaging. To convert relative gravity measurements into absolute values, an absolute gravity station at the NLCS headquarters was used; several auxiliary points were also observed so that the absolute value could be recovered if the primary station were lost.

Topographic information came from the Shuttle Radar Topography Mission (SRTM) digital elevation model, which has a spatial resolution of approximately 90 m. Because the SRTM provides heights above mean sea level, it was combined with a global geoid model (EGM96) to convert orthometric heights to ellipsoidal heights as needed. Long-wavelength variations in the gravity field were represented using a global geopotential model (EIGEN-6C4), which served as a first approximation.

1.2 Data Pre-processing

Before computing the geoid, gravity and height data were processed to isolate the regional signal of interest. Gravity predicted by the global model was subtracted from each observation to remove long-wavelength contributions. To account for high-frequency terrain effects, the SRTM topography was smoothed to remove wavelengths longer than about 20 km. The difference between the original and smoothed surfaces was used to calculate the gravitational attraction of short-wavelength topography, which was likewise subtracted from the gravity observations. These steps produced residual gravity values capturing local anomalies not represented in the global model. During this process, various cut-off wavelengths were tested; a 20 km cut-off provided a balance between reducing residual variance and retaining important regional features.

1.3 Regional Geoid Computation

With the residual gravity field in hand, the geoid surface was computed through a remove–compute–restore process. Residual gravity values were converted to residual height anomalies using least-squares collocation, an interpolation technique that models the spatial covariance of the gravity field. A covariance function was fitted to the residuals, indicating that gravity correlations extend roughly 40 km; this informed the gridding process. Height anomalies from the global model, the short-wavelength terrain contribution, and the collocated residual anomalies were summed to produce total height anomalies. These height anomalies were then converted to geoid undulations using a precise conversion formula that relates the mean gravity between the surface and the geoid. Finally, the long-wavelength part of the geoid was restored to obtain a continuous gravimetric geoid surface across Bhutan.

1.4 Vertical Datum and Model Update

The gravimetric geoid surface was aligned with the national vertical datum by fixing its undulation at a fundamental benchmark. The 2015 version of the model was tied to the TH01 benchmark at the NLC headquarters, ensuring that the difference between the GNSS ellipsoidal height and the geoid undulation matched the official orthometric height at that point. When TH01 was subsequently destroyed and a new digital levelling network established, a new reference station (THIZ) was adopted. A constant vertical shift was applied to the 2015 surface to match the geoid undulation at the new fundamental point, yielding the DRUKGEOID22 model. This update also incorporated a revised orthometric height at the Changangkha zero-order station. B-spline interpolation was used to generate a regular 0.02° grid of the updated geoid across Bhutan, ensuring a smooth surface that integrates all surveyed points. Because the bias is already embedded in the DRUKGEOID22 files, users convert GNSS ellipsoidal heights to orthometric heights by simply subtracting the geoid undulation; no additional offset is required.

2 Results

2.1 Geoid Model Overview

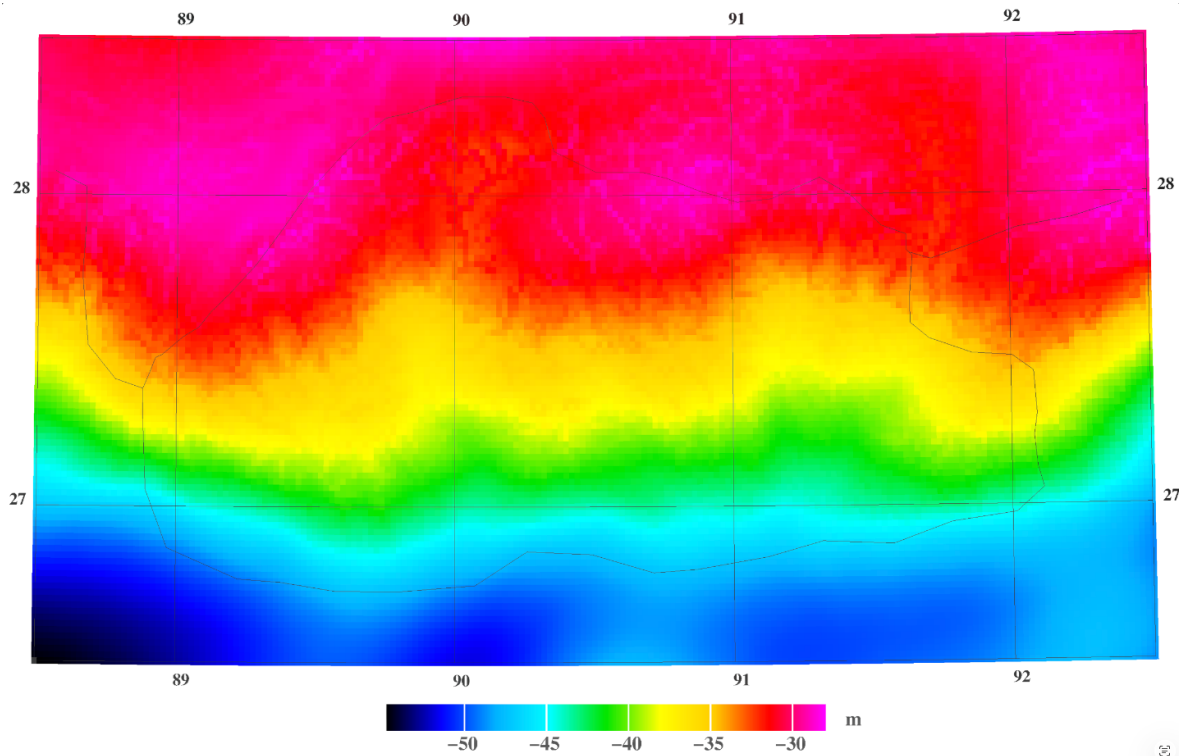


Figure 1 – DRUKGEOID22 geoid undulation over Bhutan.

The DRUKGEOID22 surface reveals a distinct north-south gradient across Bhutan. In the northern and central highlands, where the terrain is dominated by the Himalayan ranges, the geoid undulations are relatively less negative (around -30 m). Moving southward into the lower valleys and foothills, the undulations decrease to more negative values (approaching -50 m). This pattern reflects the distribution of mass beneath the surface: areas underlain by thick crust and rugged topography produce a higher geoid, while regions with thinner crust or lower elevations yield a lower geoid. A narrow buffer around the national boundary is included for interpolation; outside the area of gravity and GNSS observations, the surface aligns with the long-wavelength field of the global geopotential model.

2.2 Uncertainty Analysis

To assess the intrinsic quality of the gravimetric geoid independently of levelling errors, synthetic gravity data were generated on a regular grid using the same remove–compute–restore approach applied in the main computation. Residual gravity values were

interpolated over the region and converted into synthetic geoid undulations. Differences between these synthetic undulations and those derived from the DRUKGEOID surface were then analysed. These tests show that the geoid model achieves centimetre-level precision: in areas with dense gravity and GNSS observations, uncertainties are typically around 5 cm, while in less-observed regions—particularly along the country’s northern, eastern and western borders—uncertainties increase toward 20 cm. This indicates that the gravimetric solution itself is highly accurate and that most discrepancies seen when comparing against levelling benchmarks are due to the levelling network rather than the geoid model.

2.3 Comparison with levelling benchmarks

In addition to synthetic tests, geoid undulations were compared with heights at 27 GNSS/levelling benchmarks. The differences observed at these benchmarks have a spread of roughly half a metre, reflecting levelling errors rather than geoid errors. A comparison with an older global geopotential model (EGM96/EGM2008) shows a significant improvement: the global model has mean residuals around 1.9 m and a standard deviation of 1.7 m, whereas the DrukGeoid model reduces these to approximately 0.46 m and 0.55 m, respectively. This reduction underscores the superiority of the regional geoid relative to the global model. Nonetheless, these benchmark comparisons should be interpreted cautiously because the dispersion is dominated by the uncertainty in the levelling network itself.

2.4 Vertical datum adjustment and geoid update

After the gravimetric geoid was computed, it was aligned with Bhutan’s vertical datum by fixing its undulation at a fundamental benchmark. The 2015 geoid was tied to the TH01 benchmark, ensuring that the difference between ellipsoidal height and geoid undulation matched the official orthometric height at that point. When TH01 was destroyed and a new digital levelling network was established, a replacement zero-order station (THIZ) was adopted. The orthometric height of THIZ was precisely determined at 2436.9872 m, and this value defines the “zero point” for the updated geoid. A uniform vertical shift of 0.8761 m was therefore applied to the 2015 geoid surface so that its undulation at THIZ matched this new datum. The resulting DRUKGEOID22 grid retains the same 0.02° resolution and geographic extent as the 2015 version and includes this bias directly, so

users need only subtract the published geoid undulation from a GNSS ellipsoidal height to obtain an orthometric height.

3 Technical Information

3.1 Specifications

- **Grid format:** Regular latitude–longitude grid (ASCII and binary)
- **Component:** Geoid undulation (N)
- **Resolution:** 0.02° × 0.02° (72" × 72")
- **Coordinate order:** Latitude, longitude
- **Geographic limits:** Latitude 26.50° N – 28.50° N, longitude 88.50° E – 92.50° E
- **Coverage:** Full Bhutan extent, including a surrounding buffer
- **Interpolation method:** Bilinear (standard for gridded geoid models)
- **Fundamental point:** THIZ zero-order station (orthometric height 2436.9872 m).

3.2 Availability

The DrukGeoid22 geoid model is accessible at:

- <https://miranet.nlcs.gov.bt/public/geoid/>

It is possible the direct access to different formats:

- **ASCII (.txt)** – plain-text XYZ geoid grid listing longitude, latitude and geoid undulation values.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.txt>
- **NetCDF (.nc)** – self-describing scientific data container that stores the grid as multidimensional arrays.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.nc>
- **ESRI ASCII grid (.asc)** – raster file beginning with a header (number of rows, columns, cell size and origin) followed by row-ordered geoid values.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.asc>
- **Trimble geoid grid (.ggf)** – proprietary binary grid used by Trimble GNSS receivers and compatible software.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.ggf>
- **Leica geoid model (.gem)** – Leica binary grid with a header and geoid–ellipsoid separations.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.gem>
- **NRCAN binary (.byn)** – Natural Resources Canada binary grid with an 80-byte header and data stored row by row.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.byn>

DrukGeoid22 – Vertical Height of Bhutan

- **NGS binary (.bin)** – U.S. National Geodetic Survey binary geoid file with a one-line header and row-major data.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.bin>
- **GDAL/VDatum (.gtx)** – NOAA vertical-datum transformation grid used by PROJ and related software.
 - <https://miranet.nlcs.gov.bt/public/geoid/drukgeoid2022.gtx>

The repository also contains this report:

- **Report:** https://miranet.nlcs.gov.bt/public/geoid/drukgeoid22_report.pdf

The DRUKGEOID2022 is also accessible at the international repository of ISG (International Service for the Geoid):

- https://www.isgeoid.polimi.it/Geoid/Asia/Bhutan/bhutan2022_g.html