From DrukRef03 to DrukRef23: Grid-Based Geodetic Datum Transformation of Cadastral Parcels in Bhutan

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Key words: cadastral survey, NTv2, datum transformation, ITRF2020, CORS, deformation model, DrukRef03, DrukRef23

SUMMARY

Bhutan's first modern geodetic reference frame, DrukRef03, was realised two decades ago from a sparse network of campaign-style GNSS observations. Since then, continuing Indian–Eurasian plate convergence has introduced measurable deformation across the country, while the control infrastructure has been densified through permanent GNSS stations. Together these developments created the need for a new reference frame—DrukRef23—materialised through a national CORS network and accompanied by a transformation model suitable for cadastral use.

To support this transition, we developed a grid-based NTv2 transformation linking DrukRef03 and DrukRef23. Paired GNSS control points were used to model horizontal shifts, and an iterative filtering strategy was applied to remove outliers and stabilise the solution. The final transformation grid was generated at 10″ resolution, merging information from finer and coarser native grids to ensure continuous national coverage.

Validation shows that the model achieves sub-decimetre accuracy in horizontal coordinates, while preserving cadastral parcel areas within Bhutan's legal tolerances. The approach provides a robust and legally defensible mechanism for migrating national spatial data to DrukRef23, aligning Bhutan with international practice in tectonically active regions, and offering a flexible framework for future refinement as additional control becomes available.

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1 INTRODUCTION

Cadastral surveying and land administration require coordinates that are mutually consistent within a clearly defined geodetic reference frame. This consistency enables repeatable measurements, traceable boundary definition, and reliable integration with national spatial datasets at metre–centimetre accuracy (Enemark, 2009; Enemark, 2005; Williamson et al., 2010).

Legacy cadastral surveys referenced to earlier datums can exhibit systematic and spatially variable differences when compared with more recent realizations. Comparable issues have been reported internationally—for example, Hashim et al. (2016) describe positional-accuracy improvement during the migration from legacy cadastral mapping to digital datasets in Malaysia, and Kısa et al. (2012) analyse datum-transformation strategies for cadastral spatial data in Turkey. These cases illustrate similar technical and operational questions to those addressed here.

Bhutan's cadastral and mapping activities were referenced to DrukRef03, realized in 2003 relative to ITRF2000. National programmes – most notably the National Cadastral Resurvey Programme started in 2008 – used GPS and total-station observations under procedures set out in the Land Rules and Regulations of Bhutan (LRR, 2007). Because Bhutan lies within the Himalayan deformation zone, position differences with respect to that realization became spatially variable over time (e.g., Tashi et al., 2022).

To restore national consistency and align with current geodetic practice, Bhutan defined DrukRef23 as a static reference frame aligned to ITRF2020 at epoch 2023.5 and realized through a nationwide GNSS CORS network; this realization serves as the basis for survey and cadastral operations (e.g., Fernandes et al., 2024).

Migration of legacy coordinates from DrukRef03 to DrukRef23 cannot be satisfactorily addressed with a single similarity (Helmert/Bursa–Wolf) transformation, because such models assume a rigid-body relationship and leave location-dependent residuals in the presence of crustal strain and historical network inconsistencies. A grid-based transformation was therefore adopted: position differences are represented as corrections defined on a regular geographic lattice and applied locally during transformation. The National Transformation Version 2 (NTv2) format (Natural Resources Canada, 2021) provides this mechanism and is supported in mainstream software (e.g., PROJ/QGIS; ArcGIS) (PROJ, 2025; Esri, 2025). In Bhutan, NTv2 files are being created and applied to horizontal coordinates (latitude, longitude) to migrate legacy datasets to DrukRef23.

The transformation resources are derived from control referenced to DrukRef23 (CORS-constrained solutions and stable ground control) after quality control to remove outliers and reduce local biases. NTv2 grid-shift files are constructed at resolutions consistent with the density and quality of control; sub-grids are introduced where spatial variability requires additional detail while preserving continuity across grid boundaries. The outputs are designed for direct use in standard field and office software.

Transformation performance is being evaluated using independent checkpoints and summary statistics relevant for cadastral use (e.g., root-mean-square error, median, and 95th-percentile horizontal residuals), together with spatial diagnostics to identify localized discrepancies. Because operational consequences manifest on parcels, the work also examines how the transformation affects parcel geometry, using Thimphu District as an illustrative example, and applying the same procedure in other areas where data are available.

2 METHODOLOGY

2.1 Overview

The migration of cadastral coordinates from DrukRef03 to DrukRef23 was implemented using a grid-based transformation compliant with the NTv2 (National Transformation Version 2) standard. The workflow comprised four sequential phases (Figure 1):

1. Realization of DrukRef23. Establish the national reference frame aligned to ITRF2020 at epoch 2023.5 from continuous GNSS observations on the CORS network and align daily solutions with a Helmert transformation to IGS realizations.
2. Acquisition and curation of transformation control. Re-observe a dense subset of cadastral ground control points (GCPs) to obtain paired coordinates in DrukRef03 and DrukRef23, with traceable quality control (QC).
3. Parameterization via NTv2. Compute horizontal geographic offsets $\Delta\varphi$ (latitude), $\Delta\lambda$ (longitude) at GCPs, design and populate NTv2 grids (parent + sub-grids), and verify internal consistency.
4. Transformation and validation. Apply the NTv2 grid(s) to cadastral datasets in mainstream software and independently evaluate positional accuracy and parcel-area effects.

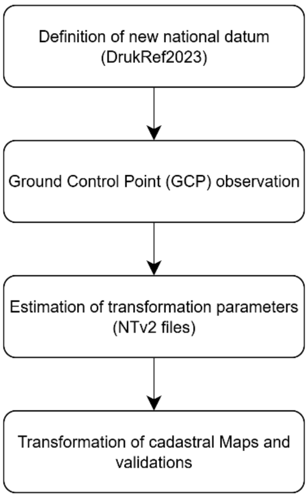

Figure 1: Workflow for nationwide NTv2-based transformation of the cadastral parcel fabric from DrukRef03 to DrukRef23.

2.2 Definition of DrukRef23 using CORS

DrukRef23 was realized from the national GNSS CORS network (DrukGeoNet), which comprises 14 continuously operating stations distributed across Bhutan (Figure 2). At each station, two weeks (15 days) of continuous GNSS tracking were collected and processed with GipsyX using a Precise Point Positioning (PPP) strategy to produce daily station solutions with formal uncertainties.

Each day's solution was aligned to ITRF2020 by estimating a seven-parameter Helmert transformation with respect to a set of globally distributed IGS reference stations. Coordinates were expressed at the reference epoch 2023.5 (1 July 2023), providing a common, time-referenced realization for all sites.

Quality control was applied at the daily-solution level prior to station-level combination. The screening criteria were: (i) magnitude of residuals to the daily Helmert fit; (ii) formal coordinate uncertainties reported by GipsyX; (iii) data completeness and continuity during the 24-hour session; and (iv) day-to-day repeatability of the estimated coordinates (WRMS/standard deviation). Daily solutions that failed these checks were reprocessed or excluded. For each station, the retained daily positions were then combined into a single weighted-average solution (weights proportional to the inverse of the formal variances), with an associated covariance estimate. For most stations, the resulting formal uncertainties were at the few-millimetre level in both horizontal and vertical components. The resulting set of station coordinates constitutes the realization of DrukRef23 used in the subsequent transformation and validation steps.

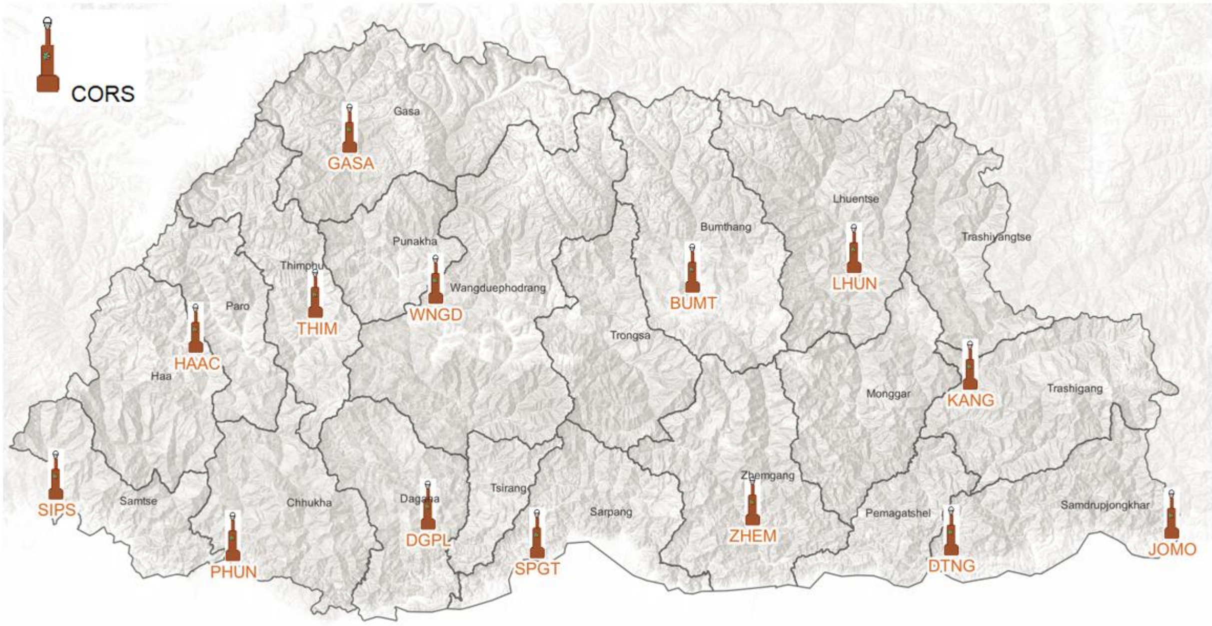

Figure 2: CORS stations forming DrukGeoNet.

2.3 Acquisition of transformation control (GCPs)

Bhutan's cadastral control network contains more than 27 000 points established during the National Cadastral Resurvey Programme (NCRP, 2008–2013). For the present transformation, a subset of 6 295 points was re-observed to serve as transformation control. Candidate points were selected to achieve approximately one GCP per 2 km × 2 km cell nationwide, with deliberate oversampling in urban areas to reflect parcel density and valuation. The 2 km grid provided a practical balance between national coverage and the control density required to support the NTv2 resolutions adopted later.

All control observations were referenced to DrukRef03, because the objective was to obtain paired coordinates for each control (DrukRef03 as source; DrukRef23 as target). Where reliable communications to the DrukNet CORS were available, points were surveyed using GNSS-RTK with network or single-base corrections. In regions without dependable CORS coverage, static sessions of at least 2 hours were acquired and post-processed; once a stable static solution had been computed, nearby points were surveyed by RTK (never exceeding 20 km) to densify local control. Field procedures recorded antenna type and height, receiver serial numbers, observation start/stop times, and solution status.

Quality control (QC) was performed before any parameterization. Checks included consistency of antenna metadata, plausibility of antenna heights, observation completeness, and solution quality (e.g., ambiguity-fixed status for RTK, formal uncertainties for static solutions). For points observed more than once, repeatability was evaluated by comparing independent solutions; outliers and points with indications of monument disturbance were set aside. Field and observational effects were mitigated at acquisition and processing by enforcing fixed-ambiguity solutions for RTK observations and by applying standard quality checks in the post-processing of campaign sessions. Residual gross errors that can still propagate into the control set (e.g., multipath, poor satellite geometry, antenna setup/centring issues, or local monument instability) were not forced into the model. Instead, their influence was controlled during NTv2 estimation by the iterative residual-based screening described in Section 3.1, ensuring that the final grid was not biased by isolated erroneous observations.

Approved records were then harmonized to a common schema comprising: point identifier; observation mode (RTK/static); timestamps; DrukRef03 geographic coordinates ($\varphi_{03}, \lambda_{03}$); derived DrukRef23 coordinates ($\varphi_{23}, \lambda_{23}$); and QC flags. This schema ensured traceability from raw observations to the paired coordinates used in grid creation.

The spatial distribution and achieved sampling density are shown in Figure 3, expressed as counts per 2 km × 2 km grid cell. The resulting control set provides nationwide coverage with increased density in urban centres, supplying the paired coordinate information required for NTv2 grid design and subsequent validation.

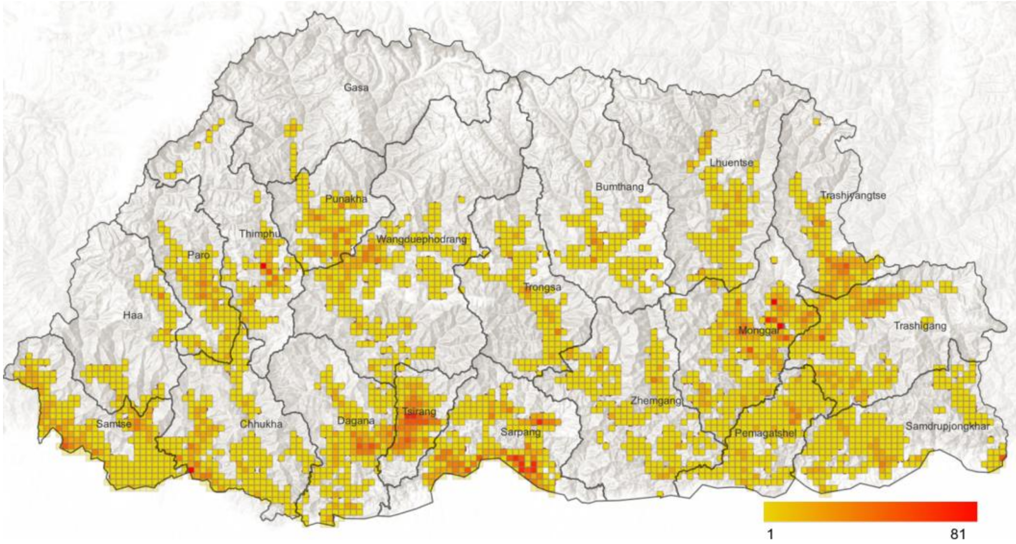

Figure 3: Map with 2 km x2 km grid cells with Ground Control Point (GCP) density.

2.4 Parameterization (creating NTv2 files)

The following step-by-step schema was adopted to create the NTv2 files:

2.4.1 Data preparation

The transformation requires paired geographic coordinates for each control point—source coordinates in DrukRef03 and corresponding target coordinates in DrukRef23. Because the legacy observations were referenced to DrukRef03, the first step was to compute differential offsets at control locations. Base stations from static sessions were processed in TBC/Carlson and constrained to nearby DrukNet CORS with known DrukRef23 coordinates, yielding precise base-station positions in DrukRef23. These solutions provided Δφ (latitude shift) and Δλ (longitude shift) between DrukRef03 and DrukRef23 at the bases stations.

The base/CORS-derived offsets were then propagated to all RTK observations (including radio-RTK), producing a uniform dataset of paired source/target coordinates for each GCP: $(\varphi_{03}, \lambda_{03})$ and $(\varphi_{23}, \lambda_{23})$. For each point, horizontal shifts were computed as:

$$\Delta\varphi = \varphi_{23} - \varphi_{03}, \qquad \Delta\lambda = \lambda_{23} - \lambda_{03}$$

Records were screened before gridding to remove cases with incomplete metadata, implausible antenna heights, large formal uncertainties, or indications of monument disturbance. Where repeat observations existed, internal consistency was checked; inconsistent entries were excluded. The resulting file contained, for every GCP, the paired coordinates, the derived Δφ, Δλ, and quality flags in a common schema suitable for NTv2 preparation (latitude-first, longitude-second ordering).

2.4.2 NTv2 grid creation

NTv2 represents horizontal coordinate differences as geographic shifts in latitude and longitude, $\Delta\varphi$ and $\Delta\lambda$, sampled on a regular grid; the shift at a location is obtained by bilinear interpolation from the surrounding nodes and applied to DrukRef03 coordinates to obtain DrukRef23 coordinates.

A single national NTv2 surface with 10″ spacing was produced from paired control-point coordinates using a multi-resolution procedure. Native grids were first modelled at spacings of 10″, 20″, 30″, 60″, 120″, 360″, 480″, 600″, and 720″, so that areas with dense, reliable control supported finer spacing while regions with sparse coverage retained a stable representation. Modelling from identical (paired) points was carried out with NTv2Creator—which applies local small-scale seven-parameter Helmert fits around grid nodes with Natural Neighbour interpolation to distribute remaining differences (Killet, 2020). Figure 4 illustrates a representative 20″ native surface used in this stage.

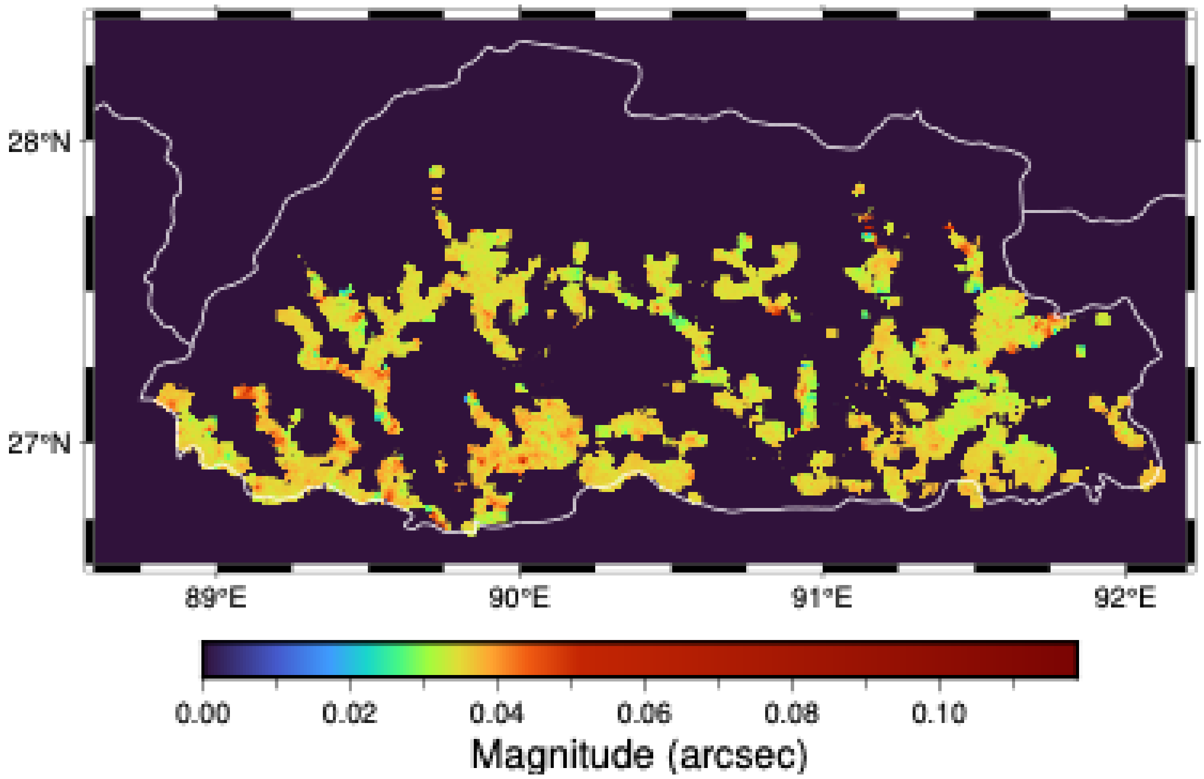

Figure 4: Native 20″ NTv2 modelling surface (DrukRef03→DrukRef23). Colors show the magnitude of the horizontal shift (arcseconds) in a region where control-point density supports 20″ modelling.

All native grids were then mapped to a common 10″ grid and—in the same operation—isolated fragments were suppressed: connected regions with fewer than 100 cells were removed to avoid tiny patches whose estimates would be dominated by one or two nearby control points and therefore overly correlated (Killet, 2020). The national resource was assembled node-by-node with a resolution-priority rule: where a native 10″ value existed it was used; otherwise the next available spacing was taken in the order 20″ → 30″ → 60″ → 120″ → 360″ → 480″ → 600″ → 720″. The coarser spacings (≥120″) extend over buffer regions outside Bhutan or over areas where no DrukRef03 data exist. Their role is to provide continuity of the transformation surface for software that evaluates a regular grid; they are not intended to supply operational transformation parameters where no legacy data exist. In this release the coarsest spacing is

720″, which ensures complete coverage across Bhutan. Coverage outside the national boundary is not required and may be partial; this has no effect on cadastral transformations within Bhutan. Coarser spacings resolve only longer-wavelength variation and therefore have lower spatial resolution than finer spacings; the workflow accordingly selects the finest spacing supported by local control-point density.

Figure 5 shows the example of 20″→10″ resampling in the same region, including the in-step suppression of isolated fragments. Layer merging and export were performed with the Generic Mapping Tools (Wessel et al., 2019) and GDAL/OGR (GDAL/OGR Contributors, 2025). The compiled NTv2 file (stored in ASCII and binary formats) records the 10″ spacing, geographic extent, and the latitude-then-longitude coordinate order expected by standard GIS software.

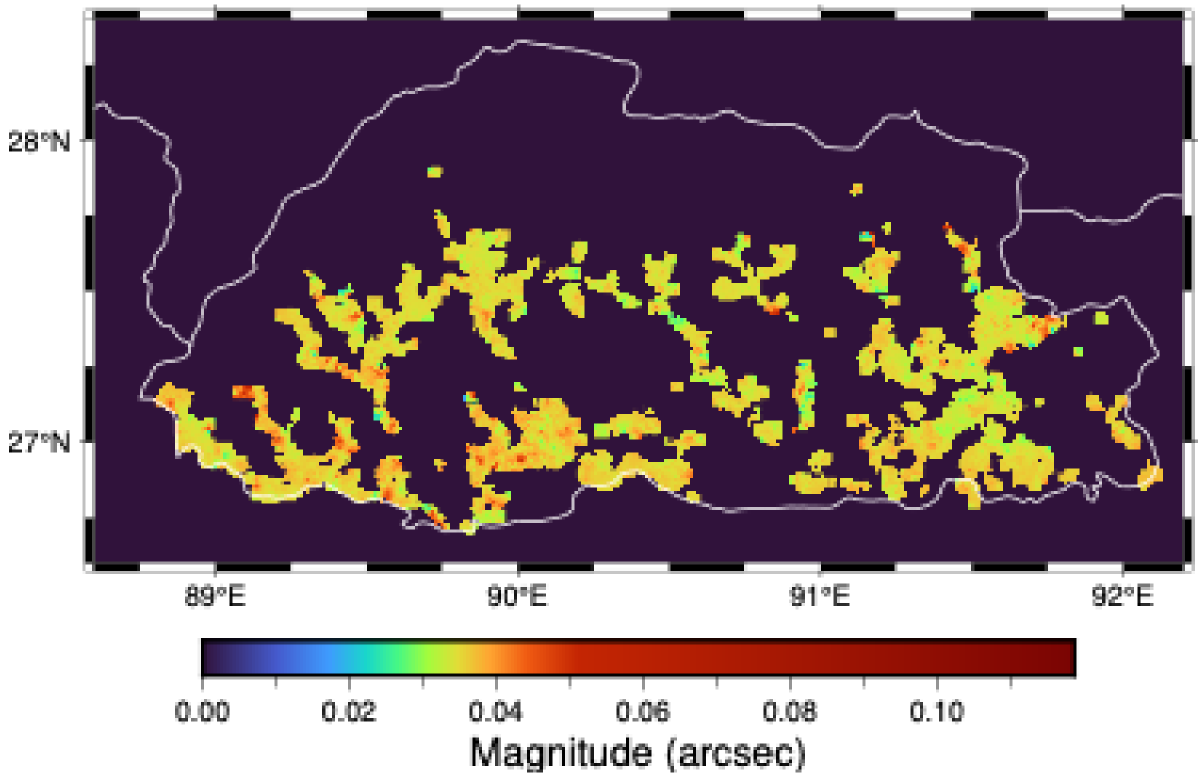

Figure 5: Resampling from 20″ to the uniform 10″ grid with in-step suppression of isolated fragments (<100 cells).

2.4.3 Cadastral Transformation

The compiled NTv2 grid is being integrated into the production toolchain. In ArcGIS Pro, it is being registered as a geographic transformation for reprojection from DrukRef03 to DrukRef23; in QGIS/PROJ, it is being used as a horizontal grid-shift resource (with bilinear interpolation). Basic configuration checks are being applied to ensure that datasets carry the correct source/target CRS and that the same NTv2 resource is referenced across projects.

A special module is under development for incorporation into MIRAnet, the management software of DrukGeoNet, to support operational use of the NTv2 file within existing workflows.

Following transformation, initial data-integrity checks are being conducted (geometry validity, essential topology consistency, and area values computed in a consistent projected CRS).

Procedures and thresholds are being finalized during rollout, and processing actions are being recorded to support the ongoing validation described in Section 3.3.

3 RESULTS

3.1 Estimation of the NTv2 file

The NTv2 transformation grid was estimated from 6 295 GNSS control points distributed across Bhutan. All computations were performed at a grid resolution of 10″, which was used both for the iterative filtering process and for the final national product. The control network accumulated over two decades of heterogeneous survey campaigns (RTK, static, different reference stations), and therefore contained outliers and locally inconsistent points. These had to be identified and removed to ensure that the grid captured systematic deformation rather than random or campaign-specific errors.

Residuals were analysed after each NTv2 solution by comparing transformed DrukRef03 coordinates against their DrukRef23 counterparts in east, north, and resultant magnitude. An iterative exclusion process was applied: in the first pass, all points with residuals larger than 500 mm were removed; subsequent iterations progressively reduced the threshold (400 mm, 300 mm, 200 mm). The final iteration retained all control points with residuals below 100 mm. At this stage, some retained points exhibited residuals slightly above 100 mm, while a few below the threshold had been flagged and excluded earlier. This outcome reflects the balance between maximising national coverage and suppressing locally inconsistent data.

Table 1 presents the final classification of points by residual magnitude. Of the 6 295 observed points, 5 753 (91.3 %) were retained for the NTv2 estimation and 542 (8.7 %) were excluded. Among the retained set, 4 974 (79.1 %) have residuals below 50 mm and 735 (11.7 %) between 50 and 100 mm. Only 44 points (0.7 %) exceed 100 mm, and these are almost all close to the threshold. Among the excluded set, 30 points fall below 100 mm (excluded in earlier iterations), 414 (6.6 %) lie between 100 and 500 mm, and 98 (1.6 %) are extreme outliers above 500 mm.

Table 1: Distribution of control points by residual class and usage in the NTv2 transformation.

Class (mm)	**Used (N)**	**Excluded (N)**
0–50	4,974 (79.1%)	–
50–100	735 (11.7%)	30 (0.5%)
100–500	44 (0.7%)	414 (6.6%)
> 500	–	98 (1.6%)

The excluded set is dominated by outliers above 100 mm, while the vast majority of retained points fall below 50 mm, demonstrating that the iterative approach efficiently separated consistent from unreliable observations. Figure 6 illustrates the spatial distribution of these residual classes. Clusters of excluded points occur in certain regions, indicating areas where inconsistent survey campaigns or local instabilities accumulated. This confirms that NTv2 interpolation can model systematic distortions but cannot accommodate random or locally erratic errors; their removal was therefore essential to obtain a transformation surface suitable for national cadastral mapping.

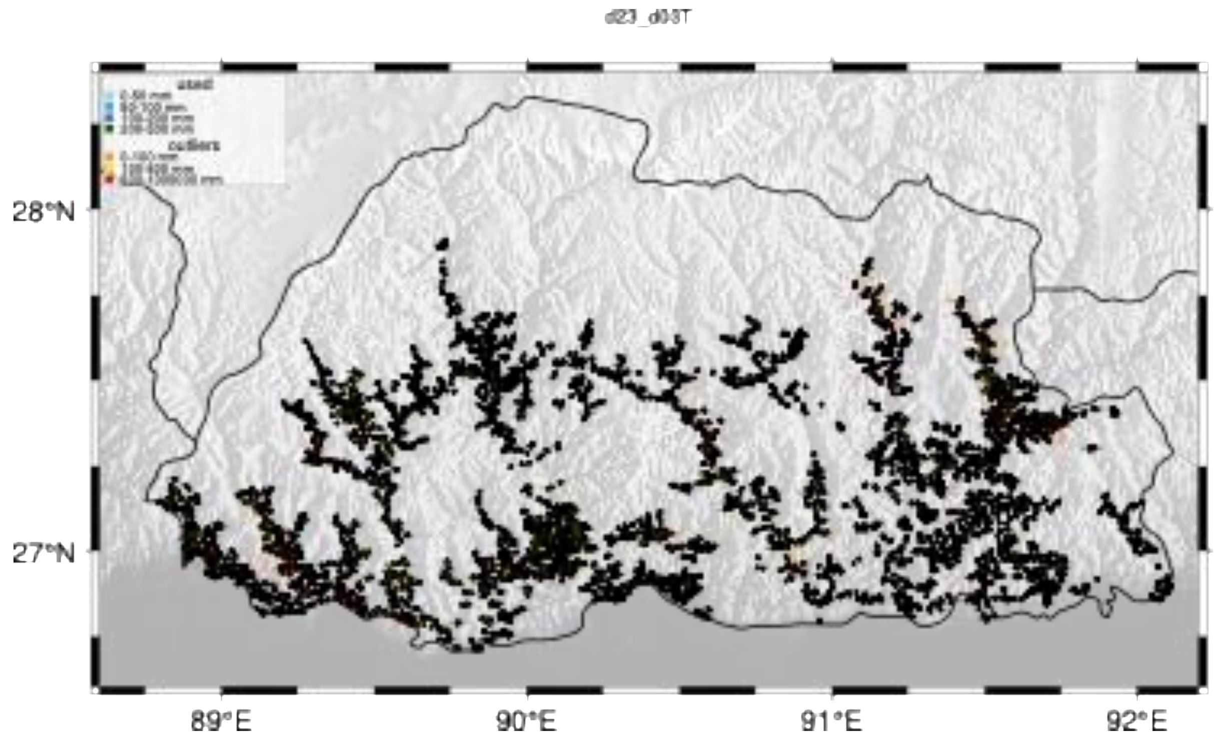

Figure 6: Residual classification of GNSS control points after iterative filtering. Colours indicate residual agnitude and exclusion status.

The final residual statistics confirm the effectiveness of the approach: the RMSE between observed and transformed coordinates is 0.021 m in Easting, 0.023 m in Northing, and 0.032 m in planar displacement. These values demonstrate that the NTv2 transformation achieves sub-decimetre accuracy, fully consistent with international cadastral mapping requirements.

3.2 NTv2 file

Figure 7 shows the final 10″ NTv2 grid of horizontal shifts (DrukRef03 → DrukRef23) across Bhutan. The field is controlled by interseismic deformation in the India–Eurasia collision zone, expressed as an ENE displacement of order one metre together with a latitude-dependent gradient—larger shifts in the south and gradually smaller shifts to the north. This internal, spatially varying deformation is the datum-change driver for cadastral applications: it creates centimeter-level inconsistencies across the country. The long-wavelength pattern accords with published GNSS deformation for the Bhutan Himalaya, while the short-wavelength structure visible in the map is attributable mainly to observational errors (the dataset of control points was created and densified over the last 20 years using different techniques - RTK, static using different reference points (always in campaign mode) which led to the propagation of errors) and occasional local control instability. Coverage within Bhutan is complete; a small no-data patch at the north-western file edge lies outside areas needing transformation.

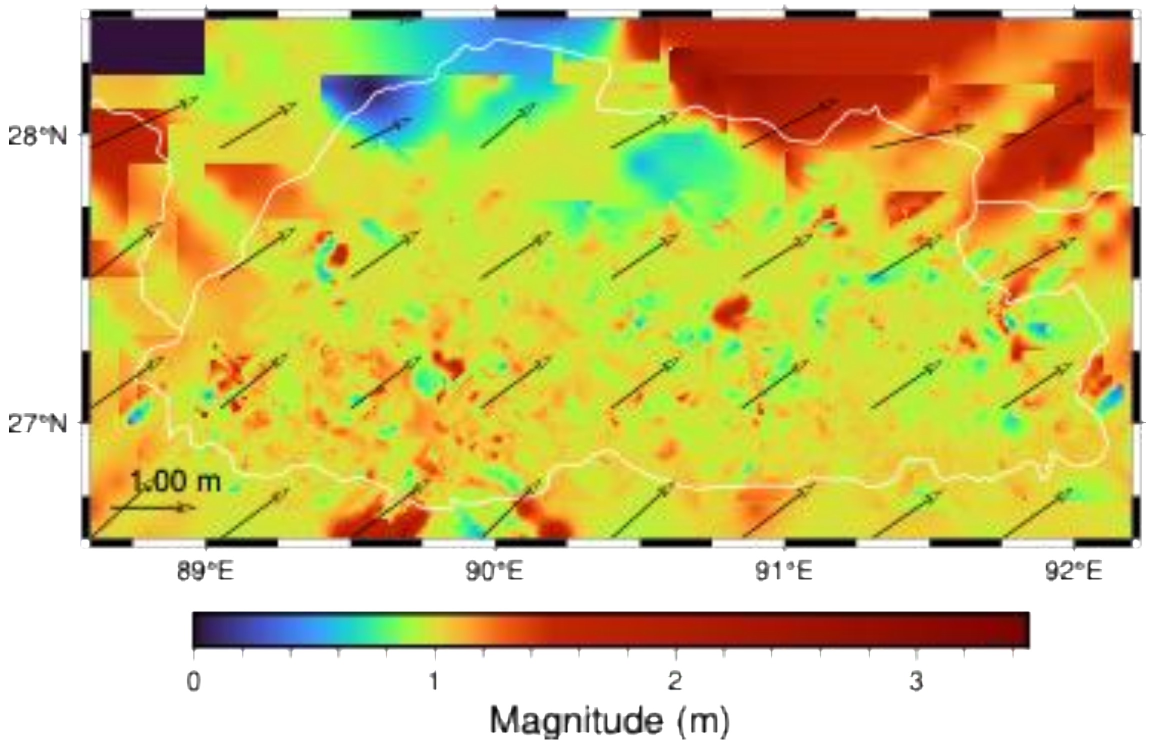

Figure 7: Final 10″ NTv2 horizontal-shift field (DrukRef03 → DrukRef23) over Bhutan.

As outlined in the methodology, native NTv2 surfaces were produced at several grid resolutions and resampled to a uniform 10″ grid to form a single final product. To evaluate internal consistency, we compared each resampled surface (e.g., 20″→10″, …, 720″→10″) with the final grid at locations where both carry values. In what follows: common nodes are 10″ nodes present in both surfaces; exact matches are nodes where both shift components equal the final value (i.e., that resolution supplies the final grid locally); differing nodes are nodes where that resolution is replaced by a finer one. Figure 8 maps the resolution actually used at each 10″ node: finer resolutions dominate where control density supports higher spatial detail; coarser resolutions provide continuity in sparsely controlled and peripheral regions. Differences for a given resolution therefore appear only where a finer resolution exists locally (e.g., 20″ differs from the final grid only where 10″ exists; 30″ differs where 10″ or 20″ exist; etc.).

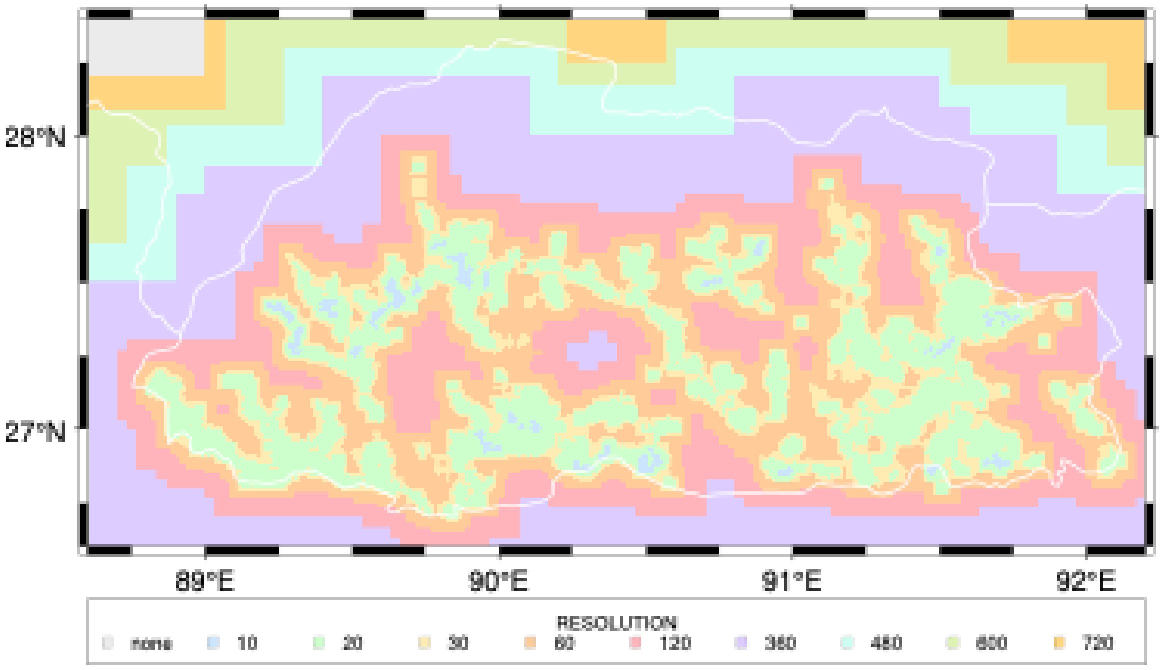

Figure 8: Resolution-of-use map for the final 10″ grid (colours show which grid resolution supplies each 10″ node).

Table 2 summarises the node-wise diagnostics. As expected, the resampled 10″ surface matches the final grid at all common nodes (6 051/6 051). For 20″–120″, where local replacement by finer resolutions occurs, magnitudes over the differing nodes are centimetre-level on average (means ≈ 0.03–0.06 m). For 360″–720″, averages rise to the decimetre level (≈ 0.10–0.18 m) with larger maxima (≈ 2.5–2.7 m). These larger values occur near resolution boundaries within the broad coarse-resolution swaths in Figure 7; they lie mostly outside Bhutan and, where inside, in areas without cadastre, so they do not affect cadastral transformation. Interpretation should rely primarily on the means and standard deviations as indicators of systematic behaviour; isolated maxima reflect a small number of boundary nodes.

Table 2: Resampled grids (resolution→10″) compared with the final 10″ grid at common nodes

Resolution (″)	Common nodes	Mean (m)	SD (m)	Max (m)	Exact matches	Differing nodes
10	6,051	0.000	0.000	0.000	6,051	0
20	110,940	0.028	0.034	0.702	105,787	5,153
30	171,366	0.025	0.029	0.759	62,090	109,276
60	299,155	0.040	0.046	1.296	129,672	169,483
120	433,344	0.059	0.064	1.193	134,939	298,405
360	657,396	0.099	0.110	2.465	224,121	433,275
480	737,136	0.155	0.197	2.527	79,778	657,358
600	804,223	0.173	0.223	2.501	67,092	737,131
720	829,655	0.184	0.233	2.653	26,824	802,831

Table 3 reports the comparison at the original node locations. Means remain at the centimetre level for 10″–120″ and increase with coarser grids (to the decimetre level for 360″–720″); maxima follow the same trend, reaching ~2.44 m at 720″. This behaviour matches Figure 7 and Table 1: where the final grid uses finer resolution locally, differences appear when contrasted with coarser originals; these larger values occur mainly in peripheral coarse-resolution corridors outside Bhutan or outside areas with cadastre, and therefore do not affect cadastral transformations within the country.

Table 3: Original surfaces compared with the final 10″ grid at coincident original nodes

Resolution (″)	Original nodes	Mean (m)	SD (m)	Max (m)
10	16,294	0.015	0.026	0.446
20	28,201	0.001	0.010	0.676
30	20,587	0.014	0.027	0.449
60	8,830	0.019	0.044	1.021
120	3,167	0.032	0.065	1.021
360	561	0.058	0.105	0.884
480	340	0.131	0.219	1.356
600	208	0.142	0.191	0.900
720	182	0.224	0.390	2.437

3.3 Parcel area integrity:

Parcel area is a legally recognised attribute in Bhutanese land administration and underpins transactions, valuations, taxation, and compensation. Even very small changes may have financial or legal implications, particularly in high-value urban contexts. To evaluate whether the NTv2 transformation introduces such effects, parcel areas were analysed in a detailed case study of Thimphu, the capital and most densely populated district. The dataset comprised 22 271 cadastral parcels, with sizes ranging from 0.01 acres to 1 193 acres.

The comparison of areas before and after transformation showed that 98 % of parcels exhibited no change at all. The remaining 2 % showed very small differences, between 0.001 and 0.006 acres, which lie well below the tolerances applied in Bhutan. The distinction between rural and urban practice is relevant: in rural areas, areas are registered in acres with three decimal places, and the observed differences are negligible at this precision. In urban areas, areas are often registered in square feet with rounded values. In such cases, the small changes introduced by the transformation can become perceptible when converted to square-foot units. This does not compromise cadastral reliability but warrants attention in future work, particularly in high-value parcels where perceptibility rather than legal tolerance may become the practical concern.

Figure 9 illustrates the transformation of cadastral data from DrukRef03 to DrukRef23 in the Thimphu case study. The analysis confirms that the NTv2 transformation preserves both positional accuracy and parcel areas to a degree that safeguards legal certainty and supports confidence in the land market.

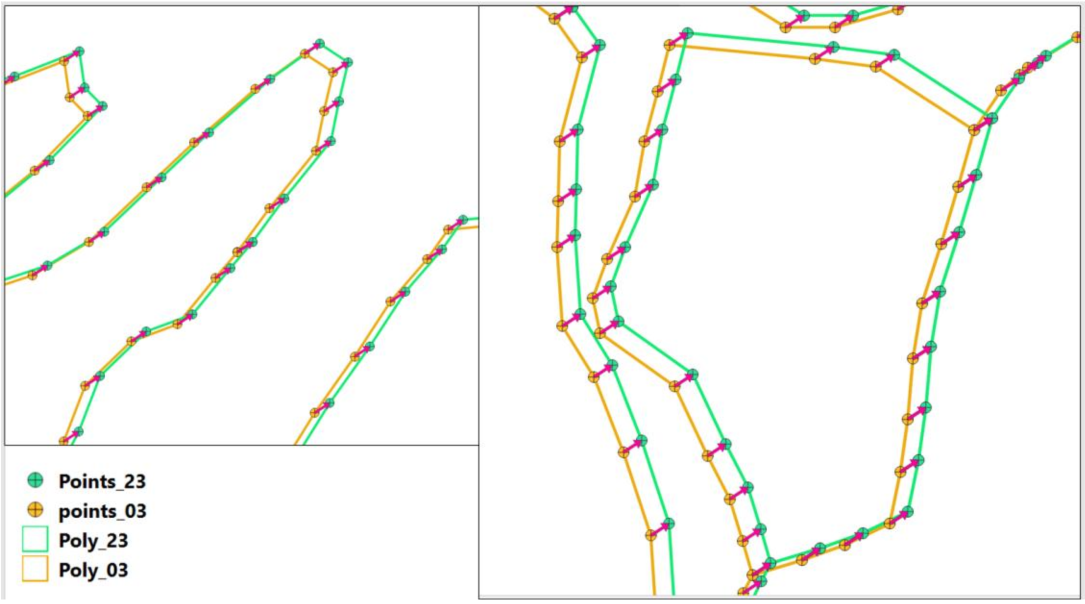

Figure 9: Cadastral data being transformed from DrukRef03 to DrukRef23.

4 DISCUSSION

Grid-based NTv2 transformations have become the international standard for managing datum updates in regions affected by crustal deformation. Australia's transition from GDA94 to GDA2020 relied on NTv2 grids to represent regionalised displacements (Geoscience Australia, 2020). New Zealand's semi-dynamic NZGD2000 integrates deformation models updated after major earthquakes to maintain cadastral consistency (Crook et al., 2016). Canada pioneered NTv2 for nationwide adoption, demonstrating its long-term interoperability and practical integration into land administration systems (Natural Resources Canada, 2021). These examples highlight that grid-based approaches are essential for ensuring cadastral and mapping continuity in tectonically active regions.

The Bhutanese case aligns with this international experience. The final 10″ NTv2 grid for the transition from DrukRef03 to DrukRef23 provides seamless national coverage while accommodating the country's non-uniform interseismic deformation. The grid preserves parcel geometry with negligible distortion: residuals between observed and transformed GNSS coordinates are at the sub-decimetre level (RMSE: 0.021 m in Easting, 0.023 m in Northing, 0.032 m in horizontal planar), well within cadastral tolerances. Parcel-based evaluation in Thimphu confirmed that 98% of areas remained unchanged after transformation, and the small number of cases with differences (≤ 0.006 acres) were below the thresholds relevant to both rural (acre-based) and urban (square-foot-based) land records. These results demonstrate that the NTv2 transformation not only satisfies technical requirements but also safeguards the legal certainty and integrity of cadastral transactions.

A further strength of the NTv2 approach is its flexibility. The final grid was constructed by prioritising finer-resolution surfaces where available and falling back on coarser solutions elsewhere, thus ensuring that local detail is preserved while national coverage remains complete. Importantly, this structure allows incremental refinement: as Bhutan's GNSS network is densified, finer-resolution patches can be recomputed and inserted into the NTv2 file without redefining the national datum. This feature is critical in a country where gradual expansion of the control network is anticipated.

Nonetheless, limitations must be recognised. The NTv2 grid is a static, fixed-epoch solution; it does not represent the time-dependent nature of tectonic motion. Bhutan lies within the India–Eurasia collision zone, where convergence produces an ENE displacement of approximately one metre over the past two decades, with a latitude-dependent gradient of ~0.1 m across the country. While this transformation resolves the internal inconsistency accumulated since DrukRef03 was adopted, positional accuracy will degrade over time as deformation continues. In the longer term, Bhutan will need to consider semi-dynamic or dynamic reference frames that incorporate velocity models, following the trajectory already taken in New Zealand and under consideration in several other countries (Wang et al., 2009).

Moreover, the present study addresses only the horizontal (2D) component of the DrukRef03→DrukRef23 transition, because the operational requirement was to preserve planimetric cadastral consistency; height differences between the two datums were therefore not analysed here. Vertical discrepancies can be locally significant, but they do not affect the horizontal transformation presented in this work. A fully modernised cadastre nevertheless requires a consistent vertical reference, since heights are legally or operationally relevant in applications such as engineering design, drainage and flood-risk management, and terrain-constraint assessment. Bhutan has already adopted an official national geoid model, DRUKGEOID22, which provides the current basis for orthometric height determination. Ongoing efforts to strengthen national gravimetric coverage, including airborne gravimetry, are expected to further refine this model. Once an updated geoid undulation surface is formally released, a vertical transformation grid can be developed using the same grid-based philosophy adopted here for planimetry (i.e., an NTv2-style correction surface for heights), enabling consistent 3D cadastral and geospatial workflows while keeping the present study focused on the validated horizontal transformation

In conclusion, the NTv2 transformation from DrukRef03 to DrukRef23 provides Bhutan with a robust, high-accuracy solution tailored to its tectonic environment. It achieves sub-decimetre residuals, preserves cadastral parcel areas, and ensures continuity in land administration while remaining flexible for future refinement. By adopting this approach, Bhutan not only resolves immediate inconsistencies in its geodetic framework but also positions itself within the international mainstream of modern cadastral geodesy.

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