

Transition to the Geoid-Based Vertical Datum and Update of the National Elevation Results

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Abstract

Japan has realized and maintained its vertical datum through national leveling campaigns on benchmarks across the entire country starting from the Origin of the Vertical Datum of Japan. However, these campaigns took more than a decade to complete, and the leveling was subject to systematic error accumulation over long distances, leading to larger estimated errors in the elevation results as the distance from the origin of the vertical datum increased. To address these problems, the Geospatial Information Authority of Japan transitioned from a leveling-based vertical datum to a geoid-based vertical datum on April 1, 2025, to update the national elevation results for the GNSS CORS network, triangulation stations, and benchmarks. This paper reports the details of the new geoid-based vertical datum of Japan, the positive impact of the transition to the new vertical datum, and the procedure for updating the national elevation results.

1. Introduction

Physical heights, including orthometric heights, closely relate to the direction of water flow, and thus are indispensable for public works on civil engineering structures and utilities such as roads, dams, water supply, and sewage. Physical heights are also required for immediate recovery and reconstruction projects for ports and embankments after major earthquakes.

On April 1, 2025, the Geospatial Information Authority of Japan (GSI) transitioned to a new vertical datum based on a global navigation satellite system (GNSS) and a gravimetric geoid model, which ensures that anyone can obtain reliable physical heights at any time and anywhere in Japan. The following sections describe the background of the vertical datum and Japan's efforts to adopt the new vertical datum.

1.1 Overview of the conventional leveling-based vertical datum

Since the introduction of modern surveying about 150 years ago, Japan has realized and maintained its vertical datum by installing benchmarks at approximately every 2 km

along major roads, repeatedly conducting national leveling campaigns starting from “Nihon Suijun Genten” (Origin of the Vertical Datum of Japan) located at 1-1 Nagata-cho, Chiyoda Ward, Tokyo, and obtaining the national elevation results, as illustrated in Fig. 1. This type of conventional vertical datum is referred to as the “leveling-based vertical datum” throughout this paper. In 1969, GSI published the national elevation results in “Adjusted Height Data for FY1969,” which covered the national territory excluding Hokkaido, the northern main island of Japan. The results for Hokkaido were published in 1972 in “Adjusted Leveling Results for FY1972.” In 2002, GSI adopted a new form of orthometric height instead of the conventional orthometric height as the physical height and published the national elevation results in “Adjusted Height Data for FY2000” (Imakiire and Hakoïwa, 2004). Since the 2011 off the Pacific Coast of Tohoku Earthquake resulted in notable crustal deformation over a wide area of eastern Japan, GSI conducted a leveling campaign in the affected area to newly publish the national elevation results in “Geodetic Coordinates 2011” (Hiyama et al., 2011).

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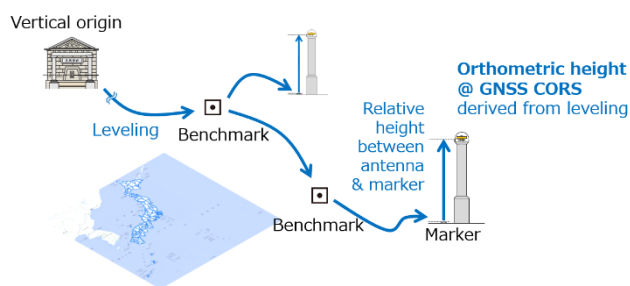


Fig. 1 Schematic for realization of the leveling-based vertical datum of Japan.

1.2 Problems with the leveling-based vertical datum

Japan used the leveling-based vertical datum for various applications for about 150 years, but this datum had the following four problems.

- 1) Leveling is a time-consuming and costly technique. As Fig. 2 illustrates, it takes more than a decade to conduct leveling surveys on the benchmarks across Japan, costing approximately 2 billion yen.
- 2) Secular crustal deformation in addition to co-seismic deformation have been observed in Japan. As these deformations continue to accumulate during national leveling campaigns, the national elevation results become inconsistent with the actual heights of the benchmarks.
- 3) Leveling is subject to systematic error accumulation over long distances, which leads to larger estimated errors in the elevation results as the distance from the origin of the vertical datum increases (Imakiire and Hakoïwa, 2004). Although the precision of the leveling surveys has improved through advancements in instrument performance and refinement of the observation methods, systematic error accumulation remains unresolved as long as we rely on repeated national leveling campaigns starting from the origin.
- 4) When it becomes necessary to update the elevation results for benchmarks following a major earthquake, long-distance leveling surveys must start from a benchmark located in an area unaffected by the earthquake. Consequently, it takes a considerably long time to publish new national elevation results for benchmarks in the affected area. For instance, following the 2011 off the Pacific Coast of Tohoku Earthquake, GSI conducted 3,660 km of leveling surveys, and it was

more than seven months before the new national elevation results were published (Hiyama et al., 2011). Under these circumstances, social demand for the timely provision of new physical heights to support rapid recovery and reconstruction following major earthquakes is not sufficiently met.

To address the problems with the time-inefficiency of spirit leveling, a geoid model GSIGEO2011 was developed to support the efficient determination of the orthometric heights of Geodetic Coordinates 2011 by GNSS surveying (Miyahara et al., 2014). However, since GSIGEO2011 is a hybrid geoid model constructed by fitting a gravimetric geoid model to GNSS/leveling-derived geoid undulations, the orthometric heights derived from GSIGEO2011 are also affected by crustal deformation and systematic errors accumulated over long distances through leveling surveys.

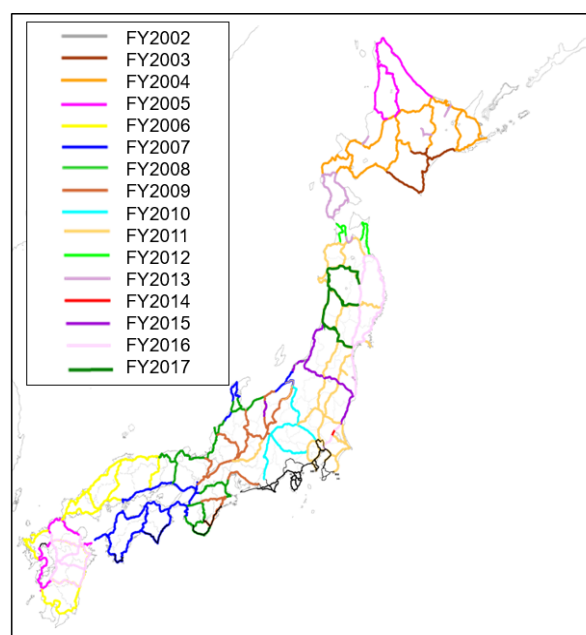


Fig. 2 Recently observed leveling routes and their fiscal years.

1.3 Global trends in the transition of vertical datum

Until the early 2010s, the leveling-based vertical datum was the only option for all countries and regions, including Japan. However, the maintenance of national leveling networks is costly, time-consuming, and laborious. For this reason, several countries have sought a transition to more cost-effective methods for maintaining vertical datums.

The adoption of the vertical datum based on GNSS positioning and a gravimetric geoid model (hereinafter

referred to as the “geoid-based vertical datum”) is an effective approach to address the maintenance problem. GNSS positioning provides the ellipsoidal height (distance from the reference ellipsoid to a point on the Earth’s surface measured along the ellipsoidal normal) rather than the physical height. Orthometric height can be obtained by subtracting the geoid height (height of the geoid surface above the reference ellipsoid) from the GNSS-derived ellipsoidal height (Fig. 3). Thus, the precision of both the ellipsoidal height and geoid height is a critical aspect of the transition to a geoid-based vertical datum. Two major technological developments — significant advances in satellite positioning and construction of a high-precision gravimetric geoid model — have enabled the transition to a geoid-based vertical datum.

In this century, GNSS including GPS and QZSS has been commonly utilized for positioning by a growing number of users around the world, and GNSS Continuously Operating Reference Station (CORS) networks have been introduced and expanded in many countries. Moreover, airborne gravimetry, which is a technique for measuring the vertical acceleration from an aircraft, has become a prevalent and reliable tool since the 2000s, thanks to the advancements in satellite positioning and inertial measurement units (IMUs). These technological trends have prompted several countries, including New Zealand and the United States, to launch nationwide airborne gravity surveys to develop high-precision gravimetric geoid models.

In 2013, Canada became the first country to officially move to a geoid-based vertical datum, CGVD2013, for the purpose of cost-effective maintenance of the vertical datum (Véronneau and Huang, 2016). New Zealand officially adopted a geoid-based vertical datum, NZVD2016, in 2024 (Land Information New Zealand, 2024). Furthermore, Australia published a geoid-based vertical datum, AVWS, on a trial basis in 2020 (Intergovernmental Committee on Surveying and Mapping, 2021), and the United States plans to adopt a geoid-based vertical datum, NAPGD2022 (National Geodetic Survey, 2025). Thus, the modernization of vertical datum is being promoted in countries around the world.

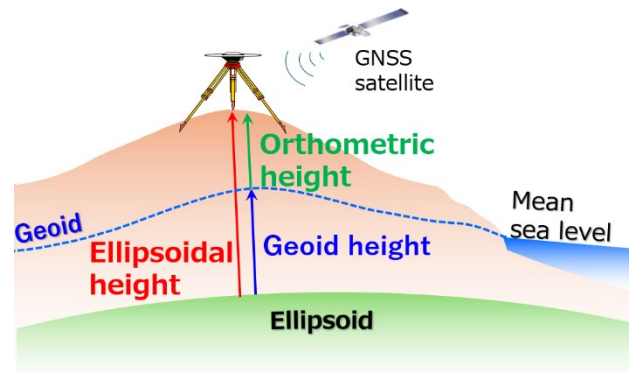


Fig. 3 Relationship between orthometric height, geoid height, and ellipsoidal height.

1.4 Japan’s efforts to transition to a vertical datum

Considering the problems with the leveling-based vertical datum of Japan and the global trends in vertical datum modernization, GSI initiated discussions in 2018 on the potential transition to a geoid-based vertical datum. While the accuracy of gravimetric geoid models depends on the quality and spatial density of the gravity data, the existing national terrestrial gravity data was insufficient for high-precision gravimetric geoid modeling due to sparse data coverage in coastal and mountainous regions and positional inaccuracies of ground-based gravity stations. To efficiently complement the existing gravity data, GSI conducted a nationwide airborne gravity survey project between 2019 and 2023, as part of its efforts to modernize Japan’s vertical datum. The survey project yielded a spatially uniform gravity dataset covering almost the entire area of Japan including its offshore islands. A new gravimetric geoid model, “Geoid 2024 Japan and Its Surroundings (JPGeo2024),” which does not rely on leveling surveys, was developed by integrating the airborne gravity data with terrestrial, shipborne, and satellite data. This model was publicly released on April 1, 2025. The geoid height calculated from JPGeo2024 is shown in Fig. 4 (for the details of JPGeo2024, see Hiraoka et al., 2026). On the same day that the geoid model was released, GSI adopted a geoid-based vertical datum in place of the leveling-based vertical datum, and updated the national elevation results for 1,318 GNSS CORS, 107,965 triangulation stations, and 15,029 benchmarks.

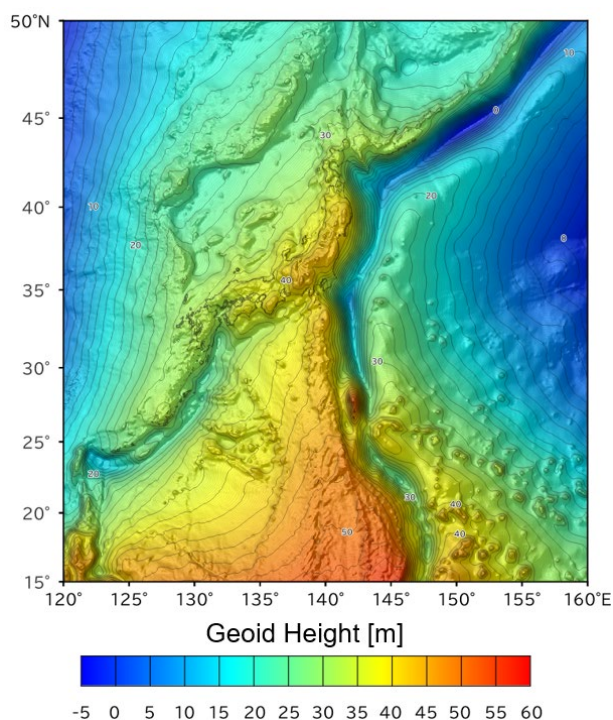


Fig. 4 Geoid height calculated from JPGeo2024.

2. Transition to the geoid-based vertical datum

2.1 Geoid-based vertical datum and its realization

Japan's new vertical datum was realized based on the JPGeo2024 gravimetric geoid model and GNSS positioning. The Survey Act (Act No. 188 of 1949) stipulates that the reference surface for the elevation in Japan is the mean sea level (MSL) of Tokyo Bay. The Origin of the Vertical Datum of Japan exists as a representation of the elevation from the MSL, which has been defined as 24.3900 m. JPGeo2024, which is perfectly aligned with the MSL of Tokyo Bay, has realized the reference surface of the elevation across Japan. Incidentally, the origin value of 24.3900 m has remained unchanged, as a recent leveling survey conducted in 2024 from Tokyo Bay to the origin confirmed that there was no significant discrepancy between the origin value and the observed elevation.

Furthermore, GNSS positioning has practically realized the elevation of each GNSS CORS by subtracting the geoid height derived from JPGeo2024 from its ellipsoidal height with respect to ITRF2014 as of June 1, 2024. This approach has realized the elevation of a GNSS CORS without relying on conventional leveling, while maintaining the origin of the vertical datum as the definition of the height reference. This means that the benchmarks and leveling network starting

from the origin in the conventional leveling-based vertical datum were superseded by the GNSS CORS and JPGeo2024 in the geoid-based vertical datum. In other words, the elevation derived from the ellipsoidal height of the GNSS CORS and the geoid height of JPGeo2024 is given the highest priority in the geoid-based vertical datum, as illustrated in Fig. 5. The reference epoch of elevation on the new geoid-based datum was designated as June 1, 2024, due to the epoch of the ellipsoidal height for the GNSS CORS. Orthometric height continues to be adopted as the physical height.

The benchmarks and leveling network are expected to be continuously maintained as national services since local governments and other public entities continue to conduct conventional leveling for precision management in areas where the distance is within 6 km from a GNSS CORS to obtain the elevation results of the benchmarks from the elevation of a survey mark neighboring the GNSS CORS.

In conformity with the transition to the geoid-based vertical datum and the update of the national elevation results, the name of the reference system was changed from “Japanese Geodetic Datum 2011 (JGD2011)” to “Japanese Geodetic Datum 2024 (JGD2024),” and the national elevation results were changed from “Geodetic Coordinates 2011” to “Geodetic Coordinates 2024.” Although the names include the horizontal datum and latitude/longitude, this update concerns only the elevation; there are no changes to the international reference system, reference epoch, or coordinates—all for horizontal components.

In conjunction with the transition to the geoid-based vertical datum and the name change of the reference system to JGD2024, GSI submitted a proposal for updating the ISO Geodetic Registry of datum, which is managed by the International Organization for Standardization, Technical Committee 211, Geographic Information/Geomatics (ISO/TC 211). The proposal has been accepted and the new Geodetic Registry identifiers are available from the official webpages of the ISO Geodetic Registry (The International Organization for Standardization, Technical Committee 211, 2026).

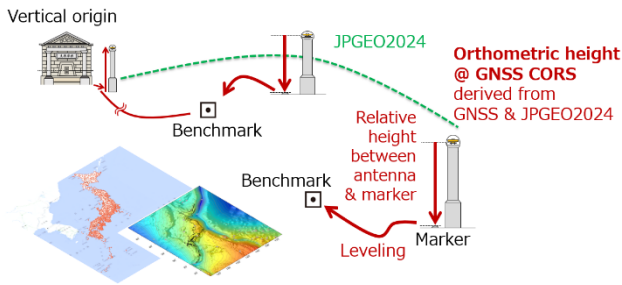


Fig. 5 Schematic for realization of the geoid-based vertical datum of Japan.

2.2 Introduction of local vertical datum offset for offshore islands

Since offshore islands separated from the mainland by sea cannot, as a matter of course, be connected to the Origin of the Vertical Datum of Japan through leveling, individual local origins have been defined to correspond to the local MSL of these islands in accordance with the Survey Act. In contrast, JPGeo2024 enables the determination of elevations referenced to the MSL of Tokyo Bay throughout Japan including offshore islands. In cases where the MSL of Tokyo Bay is adopted as the height reference for offshore islands, discrepancies of up to 1 m can be observed between the MSL of Tokyo Bay and the local MSLs. As a result, the elevations in these islands become inconsistent with the actual topographic conditions.

Considering the application of the elevation on offshore islands, the individual local origins are retained on those islands where the MSL of Tokyo Bay lies outside a standard deviation range of local tidal variations. The offshore islands where the individual local origins are retained are located at and south of the Tokara Islands or Hachijojima Island, as shown in Fig. 6. For such offshore islands, the discrepancy between the MSL of Tokyo Bay and the local MSL is defined as “local vertical datum (LVD) offset.” As illustrated in Fig. 7, the LVD offset is applied in addition to JPGeo2024 in determining the orthometric heights of the offshore islands by GNSS positioning.

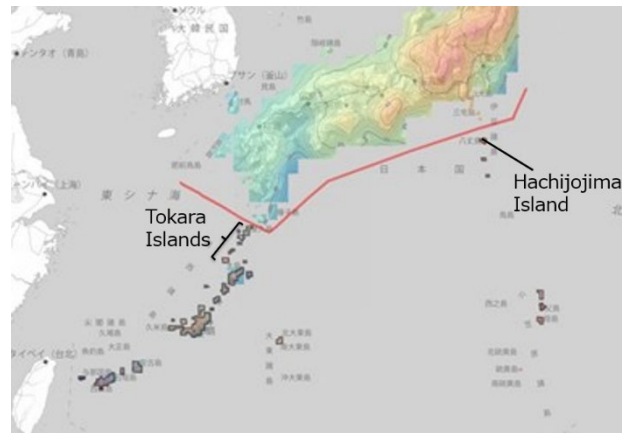


Fig. 6 Location of offshore islands where the individual local origins are retained (south of the red line).

On the other hand, for offshore islands where the discrepancy between the Tokyo Bay MSL and local MSLs is small, the vertical origin of the island is changed to the Origin of the Vertical Datum of Japan.

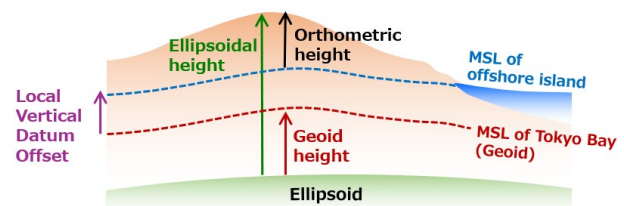


Fig. 7 Height relationship on an offshore island where an individual local origin is retained.

2.3 Positive impact of the transition to the new geoid-based vertical datum

2.3.1 Rapid provision of the national elevation results

According to our simulation, GSI will update the elevation results of a survey mark neighboring the GNSS CORS derived from the ellipsoidal height of the GNSS CORS and the geoid height of JPGeo2024 within about one month from the main shock, if no large post-seismic deformations are observed. This means that following an earthquake, local governments can initiate conventional leveling more quickly than before.

In addition, as the elevation results of the national benchmarks are determined by leveling from a nearby GNSS CORS, the distance of the leveling survey is reduced to the average spacing of the GNSS CORS (~20 km). This eliminates the need for long-distance leveling surveys over

hundreds of kilometers following major earthquakes, and enables more rapid provision of updated elevation results, contributing to the realization of a more disaster-resilient society. The elevation of a GNSS CORS, used as a reference height for the leveling surveys, is determined by the geoid height derived from the gravimetric geoid model, which is stable against crustal deformation. Regarding the temporal stability of the gravimetric geoid models, a couple of simulations imply that co-seismic geoid change in the land area is up to 1 cm even in major earthquakes such as the 2011 off the Pacific Coast of Tohoku Earthquake (Zhou et al., 2012) and the hypothetical Nankai Trough Earthquake (Kobayashi et al., 2025).

2.3.2 Elimination of accumulative errors and height discrepancies in the national elevation results

The accumulative height discrepancies due to crustal deformation during a national leveling campaign have been eliminated by updating the national elevation results associated with the transition to the new geoid-based vertical datum. Furthermore, the accumulation of systematic errors resulting from long-distance leveling surveys has also been eliminated since the national elevation results were determined from the elevation of the GNSS CORS without relying on conventional leveling.

2.3.3 Temporally consistent management of height by adopting a reference epoch of the elevation

With the introduction of a reference epoch of the elevation, the national elevation results have become uniformly consistent in time across Japan. This ensures temporally consistent management of the height as well as the horizontal coordinates through the GNSS CORS, which means that a “mechanism for management of the fourth dimension (time)” (Grant et al., 1999) is built into the datum of Japan.

3. Overview of updating the national elevation results

3.1 GNSS CORS

The national elevation results for the GNSS CORS were determined by subtracting the geoid height of JPGeo2024 from the ellipsoidal height at the reference epoch. Considering that the elevation of GNSS CORS is given the

highest priority in the geoid-based vertical datum, the maximum likelihood estimates of the ellipsoidal heights of the GNSS CORS at the reference epoch must be determined as precisely as possible. The ellipsoidal height was determined according to the following five policies.

- 1) A curve fitting approach was applied to the daily coordinates of the GNSS CORS based on the F5 analysis strategy aiming to provide the coordinates aligned to ITRF2014 (Takamatsu et al., 2023). Linear, annual, and semiannual components were used as the time functions for the fitting. The daily coordinates that were potentially influenced by snow accretion on antenna radomes and tree vegetation, as well as the outliers, were removed from the fitting. An example of curve fitting to the daily coordinates of the GNSS CORS is shown in Fig. 8.
- 2) The reference epoch of the elevation was designated as June 1, 2024, taking into account the need to minimize the influence of snow accretion and vegetation on the fitting, and to secure sufficient time to complete the work before the official release of the new national elevation results scheduled for April 1, 2025.
- 3) New antenna phase characteristic models for the GNSS CORS were developed for each combination of antenna type and antenna mount shape (Nakagawa et al., 2024) and were applied to obtain more precise daily coordinates. The new models were estimated by multiple GNSS observation sessions, while the conventional model relied on a single GNSS observation session.
- 4) The relative height between a GNSS CORS antenna and a survey mark neighboring the GNSS CORS was directly measured to precisely determine the national elevation results of the marker, which is used as a benchmark for the leveling surveys.
- 5) The curve fitting could not be applied to 25 of the 1,318 GNSS CORS nationwide in Japan, mainly because they were newly installed after the reference epoch or their coordinates were updated following a major earthquake that occurred after the reference epoch. For those stations, the national elevation results were computed with GAMIT/GLOBK (Herring et al., 2018), using one week of observation data and constraining the known coordinates of the surrounding GNSS CORS.

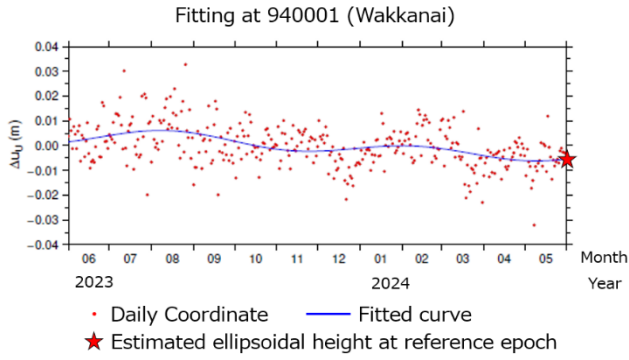


Fig. 8 Example of curve fitting to the daily coordinates of GNSS CORS, 940001 (Wakkanai). Ellipsoidal height (in meters) on the vertical axis represents the deviation from its average for the period.

3.2 Triangulation stations

Unlike the height updates in an inland earthquake, it is expected that there are no short-wavelength components that cannot be modeled by the GNSS CORS network in the height updates for triangulation stations associated with the vertical datum transition. Thus, the national elevation results for triangulation stations are updated by using a transformation grid with new and old geoid models as well as ellipsoidal height changes on the GNSS CORS without any additional GNSS campaigns on triangulation stations.

From the relationship between the orthometric height, geoid height, and ellipsoidal height (Fig. 3), the orthometric height change is given by the ellipsoidal height change minus the geoid height change. Considering this relationship, a transformation grid is generated for the triangulation stations by following the steps below.

- 1) Ellipsoidal height changes on the GNSS CORS are interpolated by the Kriging method to generate $0.5' \times 0.75'$ arc grids (approximately 1 km spacing), as with Tanaka et al. (2007).
- 2) After the GSIGEO2011 and JPGE02024 geoid heights are resampled by bilinear interpolation from $1' \times 1.5'$ arc grids (approximately 2 km spacing) to $0.5' \times 0.75'$ arc grids, $0.5' \times 0.75'$ arc grids for the geoid height change are generated by subtracting the resampled GSIGEO2011 dataset from the JPGE02024 dataset. On the offshore islands where the individual local origins are retained, the LVD offset is added to the grid for the geoid height change.

- 3) The transformation grid for the triangulation stations is generated by subtracting the geoid height change from the ellipsoidal height change on $0.5' \times 0.75'$ arc grids.

To evaluate the consistency of the transformation grid, we tested the reproducibility through a comparison of the value obtained by applying bilinear interpolation to the transformation grid against the original data at the GNSS CORS. The maximum value and RMS of the difference between the interpolated value and the source data were 9.8 and 1.4 mm, respectively.

The orthometric height changes derived from the transformation grid for triangulation stations are shown in Fig. 9. Most regions show negative values except for the Pacific coast areas of the Tohoku region, where the values of the ellipsoidal height change are positive due to post-seismic deformation.

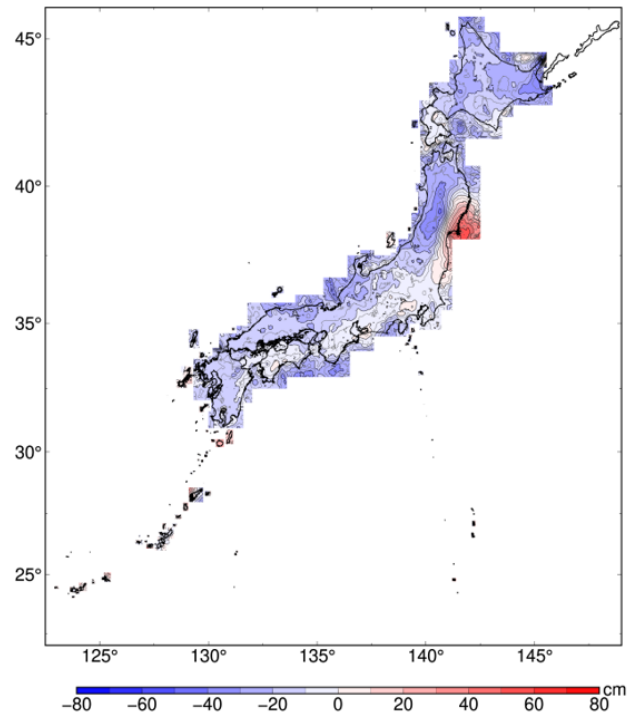


Fig. 9 Orthometric height changes derived from the transformation grid for triangulation stations.

A histogram of the orthometric height changes on the triangulation stations is shown in Fig. 10. The mean value is -13 cm, and the range is -67 to $+57$ cm, with 99.7% (3σ) of the values lying between -44 and $+19$ cm.

The transformation grid for triangulation stations is publicly available on the GSI website for use in updating the

elevation results on the triangulation stations managed by local governments.

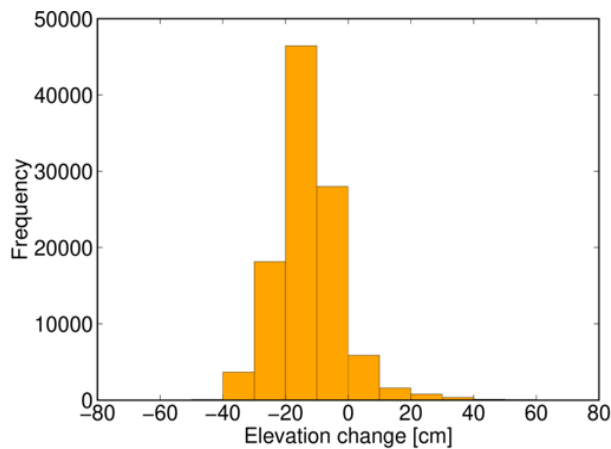


Fig. 10 Histogram of orthometric height changes at triangulation stations.

3.3 Benchmarks

The national elevation results for the benchmarks are updated to be consistent with the new elevation results for a survey mark neighboring the GNSS CORS. The fundamental idea of the update is to make an adjustment to the national leveling network while holding fixed the elevation results for a survey mark neighboring the GNSS CORS. The following two options are considered as methods for the adjustment.

- 1) A national leveling network adjustment is performed with new national elevation results, Geodetic Coordinates 2024, while holding fixed a survey mark neighboring the GNSS CORS.
- 2) First, the national leveling network adjustment is performed with the existing national elevation results, Geodetic Coordinates 2011, with the survey mark neighboring the GNSS CORS held fixed. After the adjustment, the orthometric heights on the benchmarks are transformed to Geodetic Coordinates 2024 using the height transformation grid, as illustrated in Fig. 11. The $0.5' \times 0.75'$ arc grids are generated by applying the Kriging method to the height changes from the nationally adjusted Geodetic Coordinates 2011 to the Geodetic Coordinates 2024 at 798 of the 816 GNSS CORS, which were directly connected to the conventional leveling network. The height changes of 18 GNSS CORS were not used for generating the grids,

mainly because local deformation was observed.

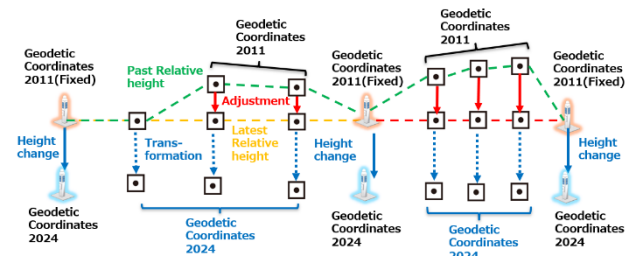


Fig. 11 Schematic of Method 2 for calculating Geodetic Coordinates 2024 for the national benchmarks.

Our preliminary verification using leveling and GNSS CORS data indicated that Method 2 was preferable in principle. Considering that the height changes from Geodetic Coordinates 2011 to Geodetic Coordinates 2024 should include accumulative deformations during the national leveling campaigns, this is presumably because the Kriging interpolation directly takes into account the spatial correlation of accumulative deformations, whereas the leveling network adjustment does not. Method 1 is exceptionally applied to the area where subsidence and volcanic deformation are locally observed.

As in the case of the triangulation stations, we tested the reproducibility through a comparison of the value obtained by applying bilinear interpolation to the height transformation grid against the original data at the GNSS CORS. The maximum value and RMS of the difference between the interpolated value and the source data were 5.8 and 1.0 mm, respectively.

A histogram of the orthometric height changes from Geodetic Coordinates 2011 to Geodetic Coordinates 2024 on the benchmarks is shown in Fig. 12. The mean value is -12.4 cm, and the range is -40.4 to $+23.1$ cm. with 99.7% (3σ) of the values lying between -36.7 and $+11.9$ cm.

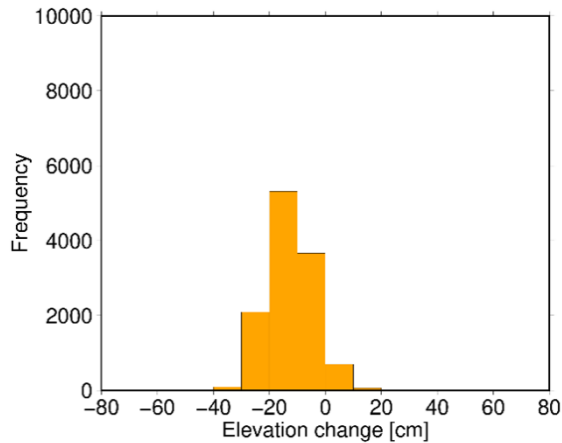


Fig. 12 Histogram of orthometric height changes on benchmarks.

GSI generated another transformation grid for updating the elevation results on the benchmarks managed by local governments to make it publicly available on the GSI website. This transformation grid is designed so that local governments can use it without being aware of whether Method 1 or 2 was applied to the target area. For this purpose, the Kriging method is applied for interpolating the changes in the national elevation results at 813 GNSS CORS and 10,885 benchmarks to generate $0.5' \times 0.75'$ arc grids.

The orthometric height changes derived from the transformation grid for local government benchmarks are shown in Fig. 13. As with the triangulation stations, most regions show negative values except for the Pacific coast areas of the Tohoku region. However, the values for the benchmarks are lower than those for the triangulation stations in the Pacific coast areas of the Tohoku region because only the national elevation results for the benchmarks have been updated in the region from FY2016 to FY2017.

The reproducibility was also tested through a comparison of the values obtained by applying bilinear interpolation to the transformation grid for local government benchmarks against the original data at the GNSS CORS and benchmarks. The maximum value and RMS of the difference between the interpolated value and the source data were 51.0 and 1.6 mm, respectively.

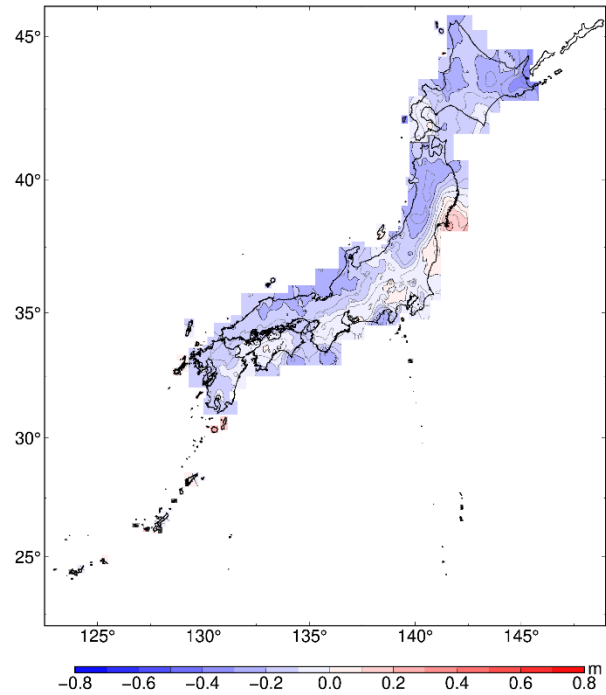


Fig. 13 Orthometric height changes derived from the transformation grid for local government benchmarks.

4. Changes brought by the vertical datum transition

4.1 ITRF and reference epoch for ellipsoidal height in GNSS processing

In the final step of static GNSS processing, the national elevation results are obtained by subtracting the geoid height (calculated by the geoid model) from the ellipsoidal height. Before the vertical datum transition, the ITRF and reference epoch for the ellipsoidal height were the same as those for the latitude and longitude: ITRF2008 at epoch 2011-05-24, in the area largely impacted by the 2011 off the Pacific Coast of Tohoku Earthquake, and ITRF94 at epoch 1997-01-01, in the other area. On the other hand, in the new vertical datum, the ITRF and reference epoch for the ellipsoidal height became the same as that for the orthometric height: ITRF2014 and June 1, 2024. The transformation between the previous ellipsoidal height and the new ellipsoidal height is possible using GSIGEO2011, the transformation grid for triangulation stations, and JPGeo2024.

4.2 Time-dependent transformation using a secular crustal deformation model, and GNSS heighting survey

Since 2010, GSI has adopted a semi-dynamic approach to implement time-dependent transformation using a secular crustal deformation model (hereinafter referred to as “secular crustal deformation transformation”) in GNSS surveys for triangulation stations. In this approach, coordinates at the reference epoch are derived from GNSS surveys using the gridded secular crustal deformation model for transformation between the observational epoch and the reference epoch (Tanaka et al., 2007). GSI adopted a simple step function as a time function in the deformation model and has updated the model once a year. The step value at the GNSS CORS is calculated by applying a curve fitting approach to the daily coordinates of the GNSS CORS based on the F5 analysis strategy (in the same manner as described in 3.1), estimating the coordinates at the observational epoch from the fitting curve, and subtracting the coordinates at the reference epoch from the estimated coordinates. The Kriging interpolation is applied for generating the gridded model from the coordinate difference at the GNSS CORS.

Even before the vertical datum transition, local governments could choose the GNSS survey to determine the orthometric height of the benchmarks. However, secular crustal deformation transformation was not applied to the GNSS survey for the benchmarks due to the absence of a specific reference epoch for the elevation. Furthermore, available GNSS CORS for the GNSS survey on benchmarks were limited to those connected to the conventional leveling network, which is approximately 850 stations.

As described in 2.1, the reference epoch of the elevation was designated as June 1, 2024 with the vertical datum transition, which ensures temporally consistent management of the heights. This means that secular crustal deformation transformation can be applied to the GNSS survey on the benchmarks maintained by local governments. In addition, all the GNSS CORS become available as known coordinates and heights for the GNSS survey on benchmarks. This enhanced GNSS survey on benchmarks is called the “GNSS heighting survey.” Local governments can choose either spirit leveling or GNSS heighting survey depending on their objectives, which will lead to improved efficiency and

productivity of surveying and public works on civil engineering structures and utilities.

After the vertical datum transition, a vertical component is newly introduced to the secular crustal deformation model. However, it is set to zero on all the grids for FY2025 because it is sufficiently small and will not have a significant effect on the GNSS surveys. The non-zero vertical component is expected to be introduced in FY2026. In addition, since the daily coordinates of the GNSS CORS based on the new F5.1 analysis strategy are to be released in FY2026, the coordinates at the observational epoch for the deformation model will also be estimated based on the new F5.1 analysis strategy from FY2026.

5. Conclusions and future prospects

On April 1, 2025, GSI transitioned from a leveling-based vertical datum to a geoid-based vertical datum to update the national elevation results for the GNSS CORS network, triangulation stations, and benchmarks. This transition was realized by a new high-precision gravimetric geoid model, JPGE02024, which represents the reference surface of elevations across Japan. The main benefit of the new geoid-based vertical datum is its contribution to strengthening national disaster resilience. Following major earthquakes, updated elevation results can now be provided more rapidly thanks to the stable operation of the national GNSS CORS and the temporal stability of the gravimetric geoid model.

In conjunction with the transition to the geoid-based vertical datum, GSI introduced the reference epoch for the heights. In other words, the coordinates of the datum in Japan are managed with temporal consistency by three-dimensional spatial coordinates and the time tag. This is the first step toward adopting fully dynamic geodetic datum, or more practically, the two-frame approach so that in the future, users can work with semi-dynamic or fully dynamic datums, similar to Australia (Intergovernmental Committee on Surveying and Mapping, 2022), although various considerations and investigations will be necessary.

Once the reference epoch for heights is introduced, three-dimensional secular crustal deformation transformation becomes increasingly important. The main challenge is improving the vertical spatial resolution of the secular deformation models, since vertical deformation can be

observed more frequently than horizontal deformation at spatial scales smaller than the average spacing of the national GNSS CORS. Our preliminary studies proposed a simple data assimilation based on the least-variance estimation for incorporating InSAR Time Series Analysis (TSA) for ALOS-2 into the deformation model, which implies that the combination of InSAR TSA and GNSS CORS contributes to improving the vertical spatial resolution of the deformation model in subsidence areas (Yamashita et al., 2022; Fukaya et al., 2023). Thus, GSI will work on operational deformation modeling using InSAR TSA and GNSS CORS in the future.

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