Development of a New Japanese Geoid Model, "GSIGEO2000"

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Abstract

GSI developed a new Japanese geoid model "GSIGEO2000" as a surface for converting from GPS-derived ellipsoidal heights to orthometric heights. Least squares collocation was applied to fit JGEOID2000, the latest gravimetric geoid model made from denser land gravity data obtained by improved calculation method, to 844 bits of geoid undulation data derived from a geoid survey (GPS/Leveling survey) conducted from 1995 to 2000.

In order to adapt the geoid undulations to the new Japanese geodetic reference system, that is, the Japanese Geodetic Datum 2000, and new national vertical datum in the orthometric height system, the GPS/Leveling data were re-analyzed in advance, in terms of leveling-derived orthometric heights and GPS-derived ellipsoidal heights with tighter constraints to the permanent GPS array of Japan, GEONET (the GPS Earth Observation Network of the GSI) in ITRF94 (epoch 1997.0) frame. The geoid undulation difference between old and new analyses ranges from – 30 to + 58 cm with a 12.5-cm SD about the mean of 5.0 cm in geoid undulation.

The signal covariance matrices for least squares collocation were determined from the analytical covariance function, which was modeled by fitting an empirical variance function from the data. The estimated error variance of the geoid undulation from the GPS/Leveling was dealt as a smoothing parameter in the process and the value which gave the smoothest result was chosen.

The formal error of the least squares collocation is about 4.0cm, and the geoid undulation discrepancies between GPS/Leveling and GSIGEO2000 range from –35.8cm at the Sata-misaki Peninsula to +23.8cm at the Nemuro Peninsula.

1. Introduction

As GPS surveys come into wide use, the need for the geoid model as a conversion surface from GPS-derived ellipsoidal heights to leveling-derived elevation has been increasing.

Dense surface gravity, topographic data and a global geopotential model can be used to construct a regional/local geoid model that is accurate for short wavelengths. However, it might have error in middle to long wavelengths due to the global geoid model used in its construction.

On the other hand, the GPS/Leveling survey (i.e. GPS measurement at benchmarks) provides the geoid undulation at the point the survey was conducted (Fig. 1). It contains geoid information for all wavelengths, but it

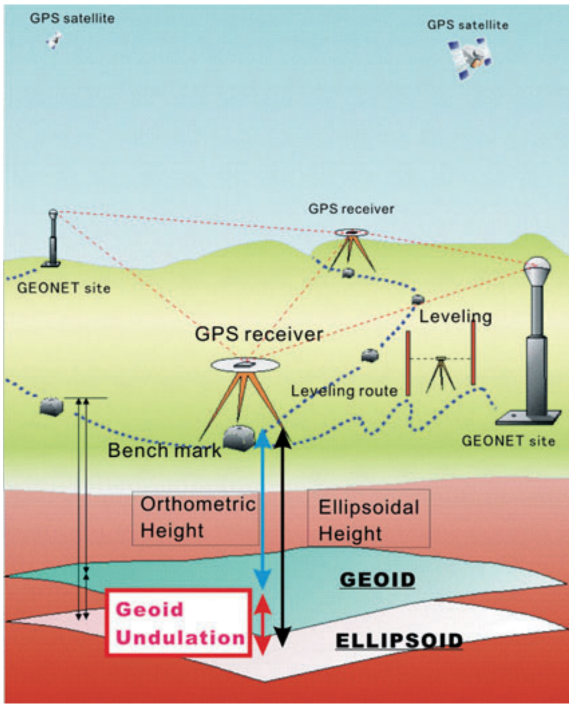

Fig. 1 Schematic figure of GPS/leveling survey.

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only determines the geoid undulation at the point the survey is conducted. Therefore, if we fit the gravimetric geoid model to the geoid undulation data from a GPS/Leveling survey, we can construct an accurate geoid model.

The geoid model constructed in this way is called "hybrid geoid model". In a strict sense, GPS/Leveling surveys provide not actual geoid height but the reference surface of the local vertical datum at the point in geocentric framework. Therefore, the hybrid geoid model actually gives the reference surface of the vertical datum. However, considering that our purpose is to give conversion parameter between ellipsoidal height and leveled height, it is suitable for practical use.

In 1997, GSI (Geographical Survey Institute) developed a hybrid geoid model of Japan, fitting a gravimetric geoid model of Japan "JGEOID93" (Kuroishi, 1995), to the geoid undulation data from GPS/Leveling survey conducted in 1995 at about 820 first-order benchmarks over Japan (Kuroda et al., 1997). However, it was mainly designed to provide geoid undulation difference to local GPS surveys and the system was not constrained tightly to the reference frame of Japan. Therefore, it was not suitable for GPS surveys with a long baseline, for example a GPS network with GEONET sites (at present, average site interval is about 20km) as control points.

In April 2002, the Japanese geodetic reference frame was replaced by a new geocentric system based on ITRF94 (epoch 1997.0) and GRS80 ellipsoid, called "the Japanese Geodetic Datum 2000" (Murakami and Ori, 1999). The vertical system was also converted from normal orthometric heights to Helmert orthometric heights. Therefore, a new geoid model which is tightly connected to the new reference frame is required.

GSI considered the new geoid model development from 1999 and decided its strategies as follows:

1) Fit the latest gravimetric geoid model, JGEOID2000, to the geoid undulation data tightly fitted to the new Japanese reference frame
2) The correction model should have a middle to long wavelength due to the nature of the gravimetric geoid model and geoid undulation data. Therefore, the discrepancy data between the geoid model and geoid undulation at the GPS/Leveling point is smoothly interpolated to create the correction model.
3) Re-analyze the GPS/Leveling data of 1995 nationwide survey, same data set as the old geoid model, and GPS/Leveling data obtained after so as to be highly constrained to the Japanese Geodetic Datum 2000.

In this paper, we first show the re-analysis of the nationwide GPS/Leveling survey data. Then we explain the procedure to make the hybrid geoid model, GSIGEO2000, by interpolating the discrepancy between JGEOID2000 and geoid undulation data by GPS/Leveling survey using the least squares collocation method. Finally, we evaluate the model. (Ando et al., 20002, Kuroishi, 2002)

2. Re-analysis of the geoid survey data

2.1 Re-analysis of GPS data

In order to conform tightly to the new Japanese reference frame, GPS data from the GPS/Leveling survey were re-analyzed and referenced to the GEONET sites in operation at the time of the observation. Simultaneously, phase-center variations were corrected and atmospheric delay was estimated to improve the accuracy of the ellipsoidal height.

2.1.1 Software

GAMIT ver. 10.04 was used for baseline analysis and GLOBK was used for network adjustment of the results. GAMIT and GLOBK were developed by the Massachusetts Institute of Technology, Scripps Institution of Oceanography, and Harvard University for scientific use.

2.1.2 GPS data

The nationwide GPS/Leveling survey was conducted in 1995. Observations were made at about 820 first-order benchmarks along the leveling route over Japan (Fig. 2). Average interval between adjacent receivers was about 20km. Four to six receivers were used in each session and observation time was three hours. Antenna types were not uniform throughout the country. In addition, we also used the GPS/Leveling survey data from

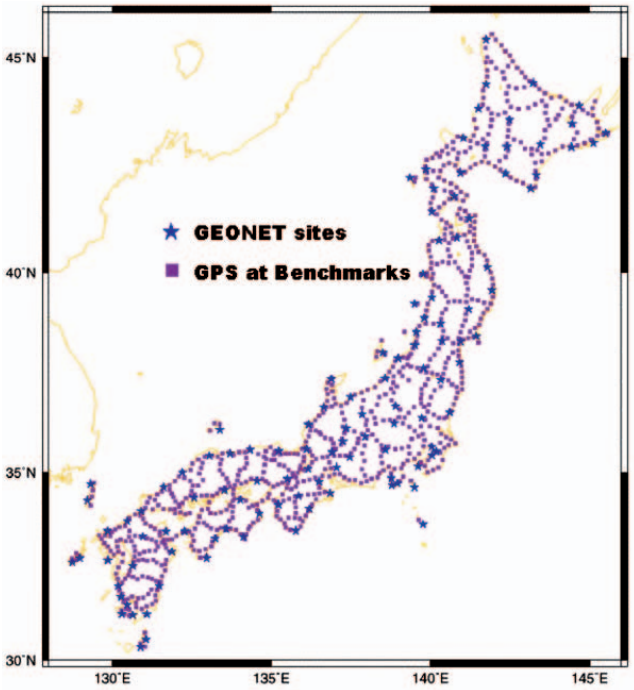

Fig. 2 Distribution of the nationwide net of GPS at benchmarks with GEONET sites.

1996 and 1998.

Then, the data of GEONET sites in operation at the time of observation was added to the data set under the following conditions:

1) In order to avoid reduction of the accuracy due to the long baseline, only the data of GEONET sites within 50km from each antenna in a session were included in the baseline analysis. However, when the RMS of the analysis was large, GEONET data were not included in the session.
2) The vertical displacement of all the GEONET sites per one year were calculated beforehand, and the GEONET sites that moved much were not used.
3) In 1995, COSMOS (i.e., Continuous Strain Monitoring System, the first GPS continuous observation network GSI developed for the Tokai and south Kanto areas. Now a part of GEONET) was in operation but only for 12 hours a day from 15:00 JST. That means COSMOS data cannot be analyzed with the GPS/Leveling data, which were taken in the daytime. Therefore, GPS observation for five to eight hours was made to connect COSMOS sites and GPS at benchmarks (or control points if they existed).

2.1.3 Baseline analysis

To improve the accuracy of the ellipsoidal height, baseline was analyzed in this way.

1) The precise satellite ephemeredes of the International GPS Service (IGS) were used.
2) For the nationwide GPS/Leveling survey in 1995, GPS three-hour data were analyzed with a sampling interval of 15 seconds. For the GPS/Leveling surveys conducted in 1996 and later, the maximum length of data observed simultaneously by all the receivers in each session was used, and the sampling interval was set to 30 seconds. The cutoff angle was set to 15 degrees for both cases.
3) The phase-center variations were corrected with the National Oceanic and Atmospheric Administration (NOAA) parameters.
4) Atmospheric delays were estimated and corrected.
5) The non-tidal system was adopted in the baseline analysis to provide consistency with the Japanese Geodetic Datum 2000, which was based on the non-tidal system.

The result of each session was adopted when the RMS was less than 0.3. Bad sessions such as when baseline analysis failed, RMS greatly exceeded the limit, or network adjustment was impossible, were either 1) divided into two parts or 2) change sampling interval, and then re-analyzed.

In some cases, especially for the sessions with at least five receivers, 1) or 2) above did not improve the result. We think this was because the baselines in such sessions were too long. Even so, we adopted the result if the free solution of GLOBK was good (zero residual).

2.1.4 Network adjustment of GPS baseline analysis by GLOBK

After baseline analysis, network adjustment was done nationwide at the same time in the following four steps using GLOBK software.

1) Calculate free solution (i.e. unfix all sites) of each session.
2) Calculate free solution of each region by combining the free solutions of the sessions in the region
3) Combine solutions of all the regions to get the free solution for all of Japan.

4) Using the free solution of 3), fix the coordinates of the 108 GEONET sites to the coordinates of the Japanese Geodetic Datum 2000 (i.e. ITRF94 (epoch 1997.0)) with a constraint of 0.01m

Finally, we got the coordinates of the 844 benchmarks where GPS/Leveling was made by referring to the new Japanese geodetic reference frame.

2.1.5 Evaluation of the GPS re-analysis

In Hokkaido and Wakayama prefectures, GPS re-observation was made at the GPS/Leveling points where the benchmark and, if eccentric observation was conducted, the position of the antenna remained. The GPS data was analyzed in the same framework as the re-analysis of the geoid undulation described in 2.1.2 and 2.1.3.

The results show that the average of the discrepancy of the ellipsoidal height between the re-analysis and the re-observation was +3.7cm in Hokkaido, +0.5cm in Wakayama and +1.1cm for all the points. The standard deviation was 2.5cm in Hokkaido, 2.9cm in Wakayama and 3.0cm for all points.

2.2 Calculation of the orthometric height at the geoid survey points

In 2002, the Japanese vertical system changed from the normal orthometric height to the Helmert orthometric height, so leveling data were re-calculated to get the orthometric height of the GPS/Leveling point. The same gravity data and same formula were used as in the re-calculation of the latest results of the leveling height at benchmarks. Simultaneous adjustment was performed for the entire network, assuming a fixed Japanese Vertical Datum Benchmark in Tokyo. The only difference was that the leveling data for calculating geoid undulation were those that were obtained nearest to the time GPS observations were made (mainly 1995) to avoid the influence of the surface movement. On the other hand, the current elevations of benchmarks were calculated from the latest leveling data.

Before calculation, we checked the record of each benchmark. Then we corrected the shift of the position if any, and determined the elevation at the position the GPS survey was performed. In the GPS/Leveling survey, eccentric observation of GPS was done at the benchmarks not suitable for GPS observation, and the height difference between the GPS eccentric observation point and the benchmark was determined by leveling for correction during the GPS/Leveling survey. We assumed the height difference had not changed since the time of the GPS survey and used the height difference value to correct the elevation.

2.3 Calculation of the geoid undulation

Subtracting the orthometric height from the re-analyzed ellipsoidal height of the benchmark gave the geoid undulations at 844 GPS/Leveling points. Then, averaging the duplicated geoid undulation data at the points where GPS/Leveling surveys were conducted in different years, we got 824 geoid undulation data which were closely connected to the new Japanese reference frame.

Fig. 3 shows the difference of GPS ellipsoidal heights, leveled heights and geoid undulation data at nationwide net of GPS/Leveling survey between the old and new analyses. The differences in ellipsoidal height range from –14 to +22cm, with a mean of 3.5cm and a standard deviation of 6.1cm. For the leveled height, the differences range from –41 to 30cm, with a mean of –1.5cm and standard deviation of 11.4cm. The differences in geoid undulation range from –30 to +58cm with a mean of 5.0cm and standard deviation of 12.5cm. The difference in ellipsoidal height was mainly due to changes in the reference GPS coordinates. On the other hand, the differences in leveled height were affected not only by the height system change but also by the crustal movements during the last 30 years.

3. Gravimetric geoid model

A gravimetric geoid model is a fundamental model for developing a hybrid geoid model. For this purpose, we used the latest gravimetric geoid model, JGEOID2000 (Fig. 5) (Kuroishi, 2001). JGEOID2000 indicates geoid undulation from GRS80 ellipsoidal surface on a grid of 1 arc-minute in latitude by 1.5 arc-minute in longitude.

Here is a brief overview of the construction of

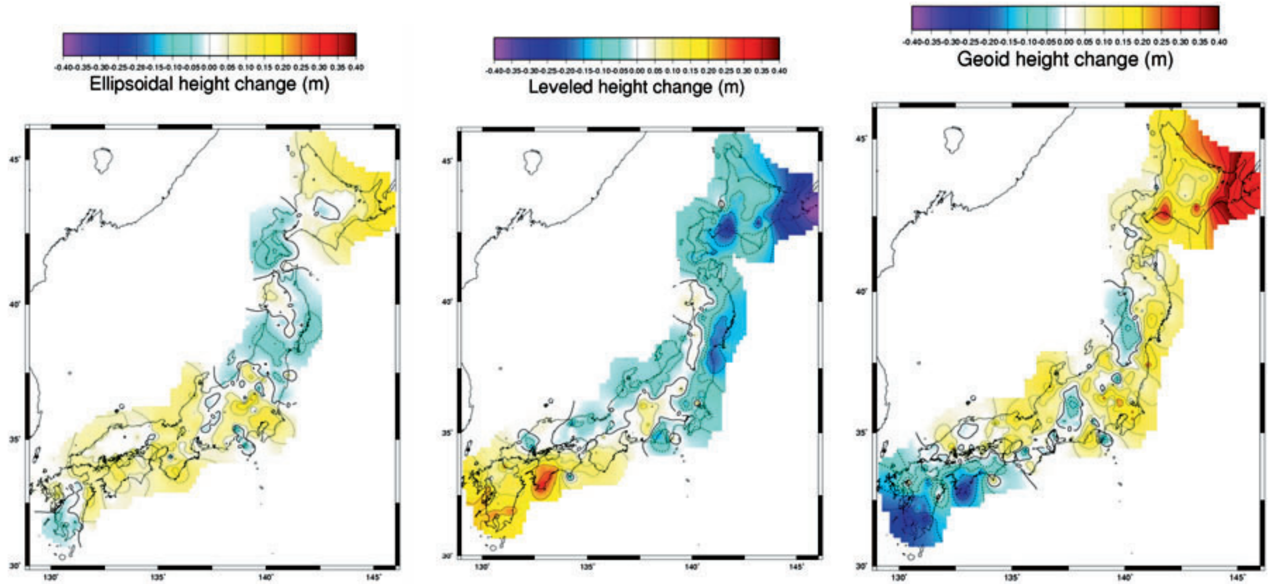

Fig. 3 The difference between the old and new analyses for GPS ellipsoidal heights (left), leveled heights (middle) and geoid undulation data (right). Color scale is –0.4m to 0.4m. Contour interval is 5cm and broken lines show contours of negative value.

JGEOID2000.

1) Global potential model, EGM96, used as a foundation.
2) Geodetic reference system: GRS80/ITRF94
3) Spherical one-dimensional Fast Fourier Transform applied to Stokes' integral. to Stokes' integral.
4) Land gravity data: about 244,000 points by GSI, Nagoya University and Geological Survey Japan.
5) Marine gravity data: about 578,000 points by BGI (Bureau Gravimetrique International).
6) Topographic data: 250m grid data by GSI

4. Combination procedures of JGEOID2000 and GPS/Leveling data

Then we fitted the gravimetric geoid model, JGEOID2000, with the re-calculated geoid undulation data described in Section 2 by least-squares collocation and constructed the new hybrid geoid model, GSIGEO2000 (Fig. 4). Consequently, GSIGEO2000 was adapted to the Japanese Geodetic Datum 2000 and orthometric height system. In this section, we explain the procedure of the model construction.

4.1 Preparation and modification for the procedure (Kuroishi, 2001)

The calculation method and process were basically the same as the old hybrid geoid model in 1996, but with

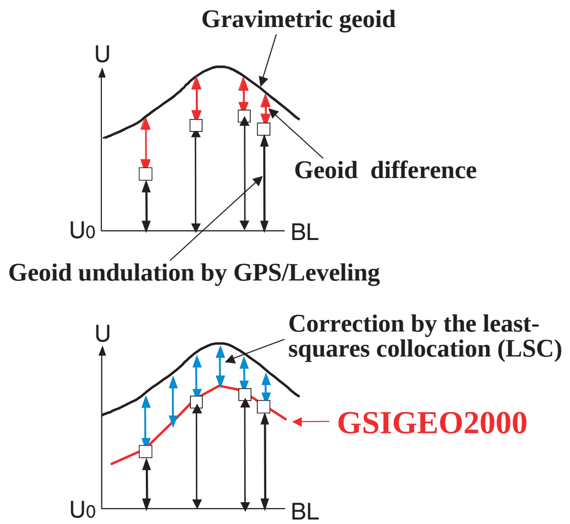

Fig. 4 Schematic diagram of hybrid geoid model construction.

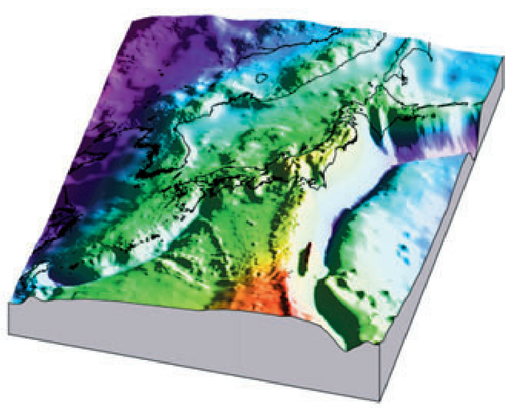

Fig. 5 Relief map of JGEOID2000.

the following improvements:

1) The coverage area was expanded to the whole area of Japan
2) Modification of the programs corresponding to the change of data grid size from 3’×3’ to 1.5’×1’ (lat.×long.)
3) Programs were prepared for randomly adding and removing range grid data from the model.
4) Modification of data format
5) Improvement of the interpolation program

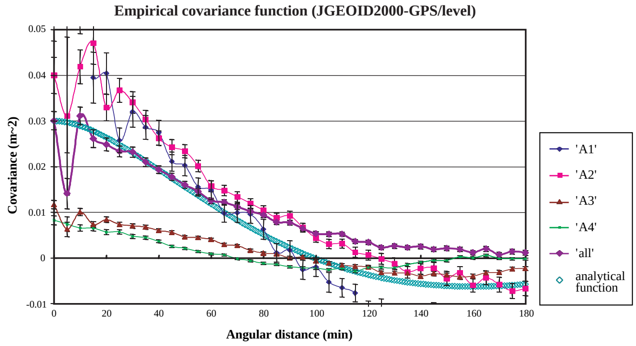

Fig. 6 Empirical and analytical covariance functions of geoid differences. A1 to A4 denote local areas.

4.2 Final process

The actual process was as follows.

1) Sort the GPS/Leveling geoid undulation data in order of the station number.

   To evaluate the model afterwards, we also made two subsets of data set called as ‘‘1’ and ‘‘2’’ dividing the entire data set (called “All”) into two halves of even and odd station numbers, respectively. Then, following the same steps as the “All” data set, we made two geoid models from each data set.
2) Subtract JGEOID2000 geoid undulation from GPS Leveling geoid undulation data (GPS/Leveling geoid undulation data–JGEOID2000 geoid undulation) and create the geoid-difference data sets. JGEOID2000 geoid undulation values at GPS/Leveling points were computed by bilinear interpolation.
3) Compute empirical covariance functions in every 5-arc-minute bin for the whole of Japan. Also, empirical covariance functions were calculated for four local areas in Japan.
4) Model an analytical function by fitting it to the empirical covariance functions calculated in 3) (Fig. 6). We used the analytical covariance function

$$C(\psi)=\frac{1}{\gamma^2}\sum_{n=N}^{\infty}\frac{A}{(n-1)(n-2)(n+24)}\left(\frac{R_B}{R_E}\right)^{2(n+2)}P_n(\cos\psi)$$

   from Tscherning and Rapp (1974).

   Parameters N, R_B and A are determined from the empirical covariance function as N=60, R_E-R_B=5,000 m and $C(\psi=0)$=0.003 m^2
5) Interpolate the geoid-difference data by least-squares collocation using the analytical covariance function determined in 4) to create the geoid-difference-grid data and its error-grid data in a 10’×10’ grid. The geoid-difference-grid data is used to corrector the gravimetric geoid model in the following process.

   In least-squares collocation, the error covariance matrix determines the smoothness of the solution. We assumed that the GPS Leveling geoid undulations are uncorrelated with each other, i.e. the matrix is diagonal with variances as diagonal elements, and treated the standard deviations as smoothing parameters. We made trial models with different standard deviations and chose the standard deviation which gave the smoothest model. More details are given in step 8).

   Fig. 7 is the corrector model from the least squares collocation and geographical distribution of its formal error. It shows that the formal error was about 4cm throughout the region except for the tips of the Shiretoko, Shakotan, and Noto Peninsulas.
6) Add the geoid-difference-grid data (10’×10’) to the gravimetric geoid model (1.5’×1’ in long. and lat.) with interpolation method, to create the hybrid-geoid-grid models.
7) Compare the difference between the GPS/Leveling data and hybrid-geoid-grid model. If there are any anomalous differences between them, then remove the GPS/Leveling data and repeat the process from 1) to 7). In this step, we removed 8 of the 824 GPS/Leveling sites.
8) As stated in step 5), we assumed the GPS/Leveling geoid undulations are uncorrelated with each other and treated their standard deviations as smoothing parameters in least squares collocation. To determine

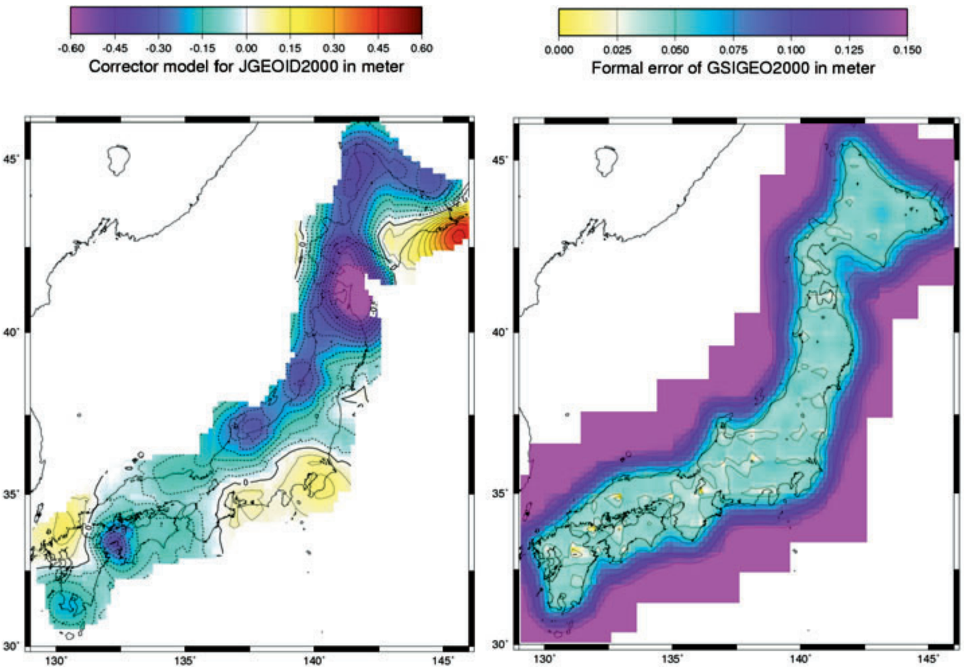

Fig. 7 Corrector model for gravimetric geoid (left) by least squares collocation and its formal error (right).

an appropriate value for the standard deviation, we made hybrid-geoid-grid-models for different values of the standard deviations ranging from 0.1 to 0.2m. Then we calculated the standard deviation of the discrepancy between geoid undulations by GPS/Leveling and the model for each model and adopted 0.13m as the standard deviation of GPS/Leveling geoid undulations, which minimized the standard deviation of the discrepancy.

5. Geoid model for isolated islands

The quality of a gravimetric geoid model is determined by the spatial density, precision and accuracy of the gravity data. For isolated islands, it differs from island to island. In addition, the gravimetric geoid model for isolated islands is dominated by marine gravity data of shallow sea areas around the islands, which tend to be biased. Consequently, the gravimetric geoid model for isolated islands can have large systematic errors. Therefore, we have to use denser GPS/Leveling points.

Thus, we made a model to correct the gravimetric geoid based on the difference between geoid undulation and gravimetric geoid. We divided islands into two categories according to the surrounding sea floor topography and the distance to the mainland. For the islands near the mainland and located on a continental shelf, the geoid-difference-grid was created by LSC with the geoid difference data of the mainland. For other islands far from the mainland and/or divided by steep sea floor topography, the geoid difference data were gridded by interpolation.

Then the corrector model was added to the gravimetric geoid to create a hybrid geoid model of the island. Finally, we replaced the island in the original model with the geoid model of the island.

For example, because Okinawa Island is located near the Ryukyu Trench and Okinawa Trough, it would be expected to have a large geoid gradient. Therefore, to correct the gravimetric geoid model and establish a hybrid geoid model of the island, a GPS/Leveling survey was conducted with denser points spaced on average about 10km apart, and we obtained 21 geoid undulation data. In addition, the geoid undulation data for four GEONET sites whose orthometric heights were determined by leveling were used. Then, geoid difference between the geoid undulation and JGEOID2000 was interpolated by spline interpolation in tension (Smith and Wessel, 1990) to create the corrector model for gravimetric geoid. We selected 0.75 as the tension parameter.

When GSIGEO2000 was first published in April 2002, it covered the Japanese mainland, Okinawa

(Kuroishi, Ando: 2001) and their major surrounding islands. We are now conducting GPS/Leveling surveys on major isolated islands and creating geoid models of these islands by considering the characteristics of the islands. These models will be inserted into the GSIGEO2000 to update the model. In the current version, GSIGEO2000 ver. 2, which was published in April 2002, twelve major islands were added to the first version (Fig. 8).

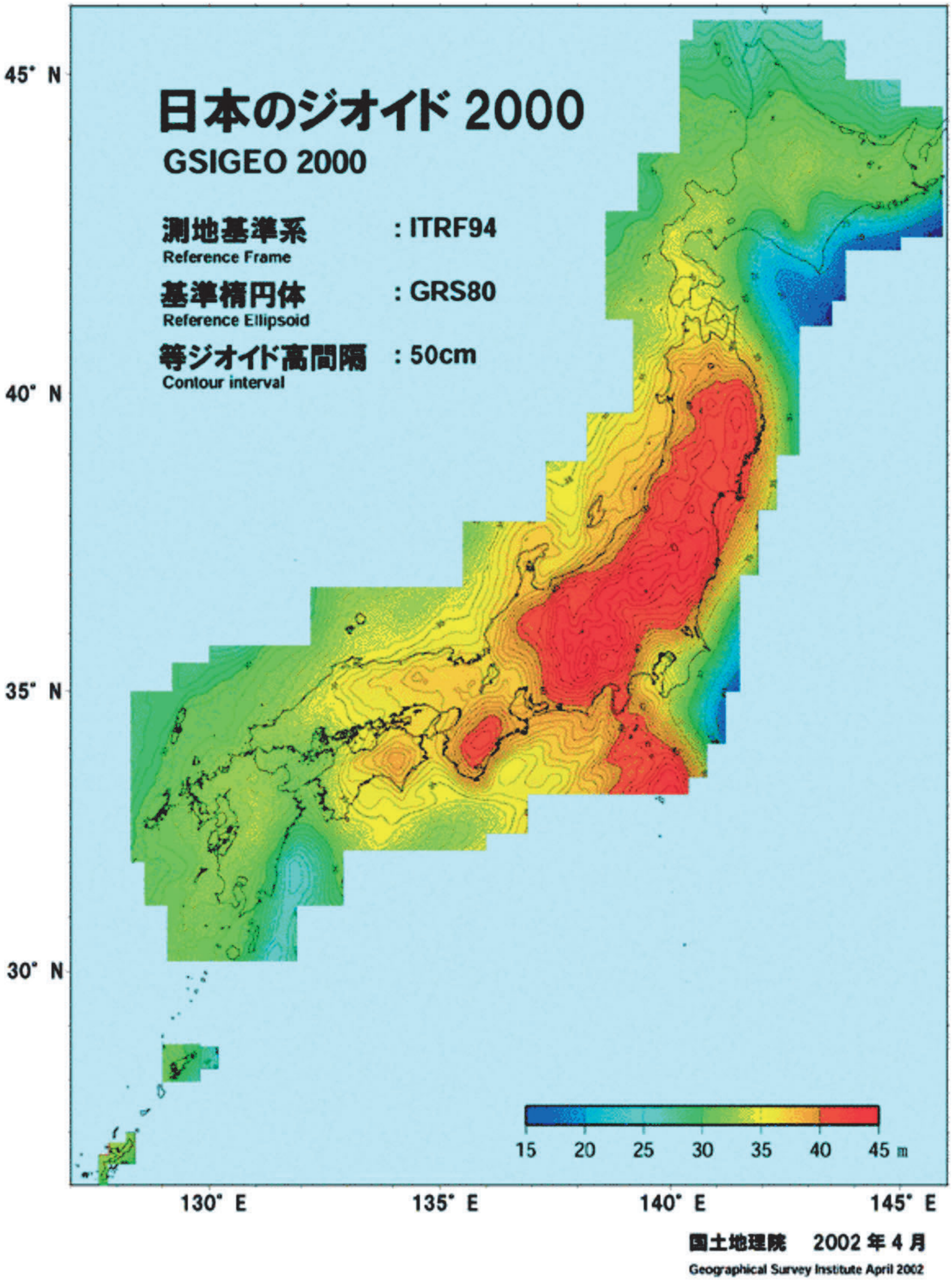

Fig. 8 Contour map of “GSIGEO2000”.

6. Evaluation of the GSIGEO2000

6.1 Comparison between the geoid undulation data and GSIGEO2000

First, we compared GSIGEO2000 with all the geoid undulation used for construction (i.e. “All” data set in Section 4.2). This means that the data and the model were not independent. Then, we made comparisons between the hybrid geoid model from the data set “1” and geoid undulation data set “2”, and geoid model from “2” and data set “1”. This case model was independent of the data. The results are shown in Table 1. The standard deviation of the geoid undulation discrepancy between the geoid undulation data by GPS/Leveling survey and GSIGEO2000 at the GPS/Leveling point is 4.0cm. The maximum discrepancy is +23.8cm at the Nemuro peninsula and the minimum is –35.8cm at the Sata-misaki peninsula. The statistics are compatible both with each other and with the formal error of the least squares collocation.

Table 1 Error estimate of GSIGEO2000

Used data set	Comp. data set	#points	Bias (cm)	SD (cm)	Max (cm)	Min (cm)
All	All	816	-0.3	4.0	23.8	-35.8
#1	#2	406	-0.8	5.4	32.6	-47.5
#2	#1	403	0	4.5	17.3	-16.4

6.2 Verification by the geoid undulation at GEONET sites

In 2000, GSI determined the orthometric heights of 50 GEONET stations in Hokkaido and calculated geoid undulations at those stations. The procedure was as follows. First, the orthometric height of the attached ground monument of the site was determined by leveling from the nearest first-order benchmark. Then, the height difference between the monument and GPS antenna was determined by GPS observation at the monument. To improve the accuracy, a 5m-high GPS antenna, same as the height of GEONET antenna, was, used and made observations for six hours. Finally, the geoid undulation was calculated by the orthometric and ellipsoidal heights of the GEONET.

Comparing this data to the GSIGEO2000, we found that the discrepancy ranged from –3.9cm to +25.4cm with a standard deviation of 6cm. The discrepancy was within the range of +/–4cm. for the stations installed in 1994, which was used for the development of the GSIGEO2000.

7. Summary

To combine the gravimetric geoid model JGEOID2000 with the geoid undulation data by GPS/ Leveling, a new hybrid geoid model of Japan, GSIGEO2000, was constructed. GPS/Leveling data were re-analyzed based on the Japanese Geodetic Datum 2000 and Helmert orthometric height system. The internal evaluation and the evaluation by independent data show that the precision of GSIGEO2000 was about 4cm for nearly the entire region.

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