Realization of Horizontal Geodetic Coordinates 2000

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Abstract

This is a record of the realization of the new Japanese Geodetic Datum 2000 (JGD2000), giving specific descriptions of how the Geographical Survey Institute calculated the new Geodetic Coordinates 2000 of horizontal control points including VLBI and GPS permanent stations based on the philosophy and definition of JGD2000. Re-calculation of coordinates of over 100,000 horizontal control points is not an easy task. Its preparation goes back to the early 1990s. Due to the wide variety of survey data and constraints on time and resources, this calculation is not straightforward and is full of trials. For the ease of general readers, this review provides a streamlined calculation procedure of Geodetic Coordinates 2000 of horizontal control points, focusing on their traceability back to ITRF94.

1. Overview

Following the revision of the Survey Act in June 2001, the century old Tokyo Datum has been legally superseded by the brand-new JGD2000 since April 1, 2002. JGD2000 is compliant with the International Terrestrial Reference System (ITRS) maintained by the International Earth Rotation and Reference Systems Service (IERS). To express longitudes and latitudes, a reference ellipsoid of GRS80 is employed in place of the Bessel ellipsoid of the Tokyo Datum.

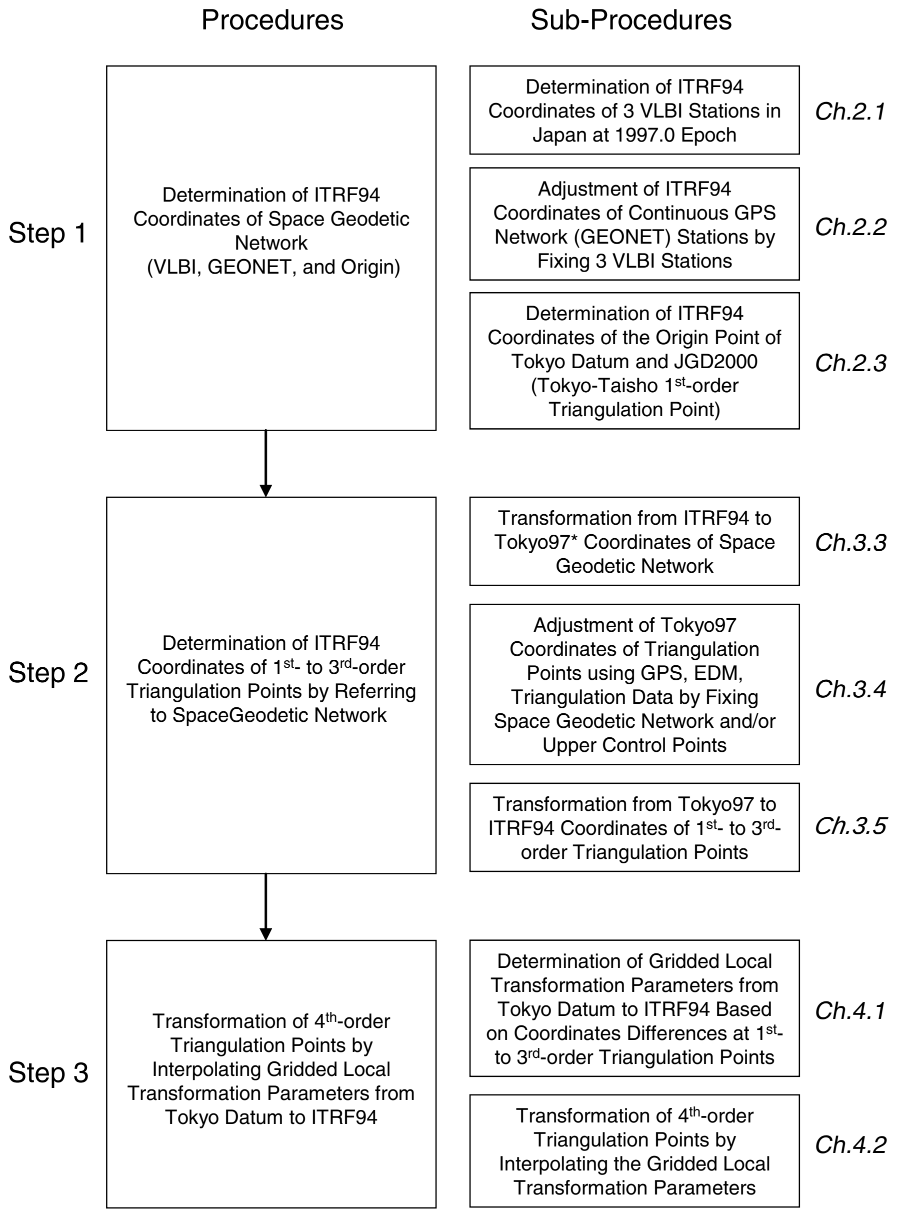
Space geodesy played a key role in introducing JGD2000, because it revealed that the Tokyo Datum had an origin shift of about –146 m, 507 m, and 681 m in X, Y, Z components with respect to ITRS, and that the old geodetic network suffered from internal distortions up to several meters due to accumulation of crustal deformations and inevitable survey and calculation errors at that time. JGD2000 is realized by fixing the positions of three VLBI stations in Japan with the International Terrestrial Reference Frame 1994 (ITRF94) coordinates at the epoch 1997.0, which was the latest realization of ITRS when we defined JGD2000 in 1997 (Murakami and Ogi, 1999).

Now the Geographical Survey Institute (GSI) provides newly adjusted coordinates named Geodetic Coordinates 2000 of GPS-based control points (GEONET; about 1,200 points) and the 1st- to 3rd-order triangulation points (about 38,000 points), together with transformed coordinates of the 4th-order triangulation points (about 64,000 points). To establish the new geodetic system, re-surveys of such points have been carried out by Electro-optical Distance Meters (EDM), then the Global Positioning System (GPS), since 1974.

Fig.1 shows the calculation flow of horizontal Geodetic Coordinates 2000. Here we touch on each step, followed by detailed descriptions at the chapters mentioned in the figure.

Step 1 is the determination of the framework of JGD2000, calculating ITRF94 coordinates of VLBI and GPS permanent stations. Since the legal definition of JGD2000 follows a classical style, i.e. by specifying one horizontal datum origin with its defining parameters, the 1st-order triangulation point at Tokyo-Taisho is included in the framework network as the de facto origin of JGD2000 (plate 1).

Step 2 is the densification of JGD2000 at the 1st- to 3rd-order triangulation points by adjusting their coordinates to fit the most recent survey data available at each point, fixing the coordinates of the framework space geodetic network. Depending on the order and location of points, the most recent data range from the latest GPS surveying, modern EDM trilateration, and classical triangulation. To complicate the matter, the actual network adjustments are conducted in an intermediate reference frame named Tokyo97, not in ITRF94. Although the longitudes and latitudes of triangulation points are revised with the introduction of JGD2000, their heights above sea-level are not changed because they are independent of the selection of a reference ellipsoid.



* Tokyo97 is defined as the intermediate reference frame that has the same ellipsoid (i.e. Bessel) and origin (i.e. Tokyo-Taisho 1st-order triangulation point) as the Tokyo Datum, and the same orientation and scale as ITRF94.

Fig. 1 Flow of Calculation of Horizontal Geodetic Coordinates 2000

Step 3 is the determination of Geodetic Coordinates 2000 of the 4th-order triangulation points, which have been established to promote cadastral surveys since the 1950s. Since re-adjustment of survey data at these 64,000 points was not realistic in addition to the Step 2 procedure, GSI decided to take the second best by introducing a precise datum transformation program that uses local transformation parameters determined from the coordinate differences of the 1st- to 3rd-order triangulation points between JGD2000 and the Tokyo Datum.

Details of this calculation are documented in Japanese references on Geodetic Coordinates 2000 (e.g. Notazawa, 1999; Takahashi, 1999; GSI, 2003a). This paper provides a review on the calculation procedure of horizontal Geodetic Coordinates 2000 for general readers.

2. Horizontal Geodetic Coordinates 2000 of Space Geodetic Network

Space geodetic techniques have shown a remarkable development in the past two decades and enabled the geodetic/geophysical communities to conduct truly global observations with unprecedented precision. Their internal precision in coordinate determination has reached a few mm to 1 cm at present. GSI started experimenting with these techniques in the early 1980s and as their precision and reliability were established through number of experiments and observations, successfully constructed nationwide space geodetic networks of VLBI and GPS. Japan is now covered by one of the densest space geodetic networks in the world.

After GSI's decision to revise Japan's geodetic reference in 1993, the first step was to establish the fundamental network of new frame by space-geodetic techniques. This chapter describes the process, data and results of the endeavor. The major part of calculation was completed in 1997.

2.1 VLBI

2.1.1 Brief History of GSI's VLBI Activity

GSI began to utilize VLBI technology for geodetic surveys in 1981 by developing a transportable VLBI system with a 5 m antenna fully supported by the Radio Research Laboratory (RRL), which was reorganized as the Communications Research Laboratory (CRL) in 1988, a pioneer of VLBI technology in Japan. The first experiment was conducted using the 5 m antenna system at Tsukuba and the 26 m antenna at RRL's Kashima branch in 1984. Then, mobile VLBI experiments were conducted from 1986 to 1994, between 10 sites (9 in Japan and one in the Republic of Korea) and Kashima. GSI also developed more compact systems with 2.4 and 3.8 m antennas during that time. In 1992 the ownership of the Kashima 26 m antenna was transferred from CRL to GSI and GSI shifted its VLBI strategy from mobile to fixed observations with larger antennas and began to actively engage in international experiments with the 26 m antenna (Plate 2). GSI newly built 4 fixed stations in Shintotsukawa, Tsukuba, Chichijima and Aira. Rapid development of GPS technology and expansion of its network for geodetic observations in the late 1980s and early 90s caused geodetic VLBI to become a fundamental reference tool for geodetic systems. Kahisma-26m was dismantled in 2003 because of its aged equipment.

At present, GSI operates 4 fixed stations and while conducting monthly domestic experiments, participates in more than 50 international experiments with Tsukuba-32m as the successor to Kashima-26m. For data analysis, Calc/Solve developed by NASA/GSFC has been used for domestic data reduction. The International VLBI Service for Geodesy and Astrometry (IVS) takes care of international experiments and provides Earth Orientation Parameters (EOP), Terrestrial Reference Frame (TRF), and Celestial Reference Frame (CRF) products to users in the world. Table 1 summarizes mobile VLBI experiments and Table 2 is the list of fixed stations.

Table 1 Mobile VLBI experiments of GSI

Site name	Year	Antenna diameter	Fixed station
Tsukuba	1984 - 1991	5m	Kashima 26m
Shintomi	1986, 1988, 1993	5m	
Chichijima	1987, 1989	5m	
Shintotsukawa	1990	5m	
Mizusawa	1991	5m	
Sagara	1992	5m	
Kanozan	1993, 1994	* 2.4m	Kashima 34m
Kainan	1993	5m	26m
Tonami	1994 *	* 2.4m	34m
Swon **	1995	3.8m	26m

* single frequency experiments; ** in the Republic of Korea

Table 2 Fixed VLBI stations of GSI

Name	Operation period	Antenna diameter
Shintotsukawa	1996-	3.8m
Tsukuba	1998-	32m
Kashima	1967-2002	26m
Chichijima	1997-	10m
Aira	1997-	10m

2.1.2 Network and the Reference Point for JGD2000

VLBI stations relevant to the construction of JGD2000 are shown in Plate 3. Kashima-26m was chosen as the origin of the framework of JGD2000 as it had a long history of international and domestic observations. Its position and velocity had been determined with high precision through international projects such as CDP, DOSE and CORE since 1984.

The reference epoch for JGD2000 was determined as 1997 January 1, 0h UTC (1997.0) and the position at

1997.0 of Kashima-26m in the latest global frame, ITRF94, was chosen as the reference of the new geodetic system.

Here are the position (m) and velocity (m/year) of Kashima-26m as of 1993.0 in ITRF94 by IERS.

X: −3997892.2680 ±0.0070
Y: 3276581.2620 ±0.0070
Z: 3724118.2880 ±0.0089
Vx: −0.0018 ±0.0019
Vy: 0.0014 ±0.0016
Vz: −0.0144 ±0.0021

We adopted the following values for the position of Kashima-26m at 1997.0 by adding the changes, i.e. velocity multiplied by 4 years, to 1993.0 values.

X: −3997892.2752
Y: 3276581.2676
Z: 3724118.2304

These values were held fixed for the domestic VLBI analysis and the adjustment of the fundamental network for the new geodetic system.

2.1.3 VLBI Data and Connection to GPS Network

We considered long baselines determined by VLBI provide fundamental set of data for the framework of JGD2000. Five mobile sites (Mizusawa, Sagara, Kaian, Shintomi and Chichijima) and one fixed station (Shintotsukawa) were used for the evaluation of VLBI-GPS combination. In the combination and comparison of VLBI data with GPS or traditional survey data, connection to GPS observation point or ground marker had to be precisely determined. The reference point for VLBI is at the intersection of the azimuth and elevation axes. Although the method varied between small antennas (direct) and large ones (indirect), relative vectors from the nearby ground marker to the VLBI reference were determined within a 1 cm accuracy (GSI, 2003a).

Comparing VLBI solutions by Calc/Solve with GPS (nearby GEONET + connection) solutions, we chose 2 other VLBI sites, Shintotsukawa (not mobile) and Kainan (mobile) along with Kashima-26m, for the fixed points in the adjustment with GEONET. Below is the treatment of VLBI sites in the fundamental adjustment.

- Shintotsukawa: Fixed. Regular experiments since 1996.
- Mizusawa: Adjusted. Only one mobile experiment.
- Sagara: Adjusted. Only one mobile experiment.
- Kainan: Fixed. However, only one experiment was conducted at this site, suitable for the fixed point for the western part of Japan. Kashima's velocity was used for the reduction of position to 1997.0.
- Shintomi: Adjusted. Site position changed after 2 big earthquakes nearby in 1996.

In Table 3 the positions of VLBI reference marker on the ground are listed. Table 4 is the relative vectors from the ground markers to Kashima-26m. KS-13 was adopted for later calculation.

Table 3 VLBI reference positions in ITRF94

Site name	Epoch	Position (m)	
Shintotsukawa	1997.0	X	−3642139.6683
		Y	2861494.7501
		Z	4370358.9025
Shintomi	1997.0	X	−3582765.6676
		Y	4052031.4359
		Z	3369018.3817
Kainan	1997.0	X	−3751040.3551
		Y	3721052.3198
		Z	3560816.7309
Mizusawa	1993.0	X	−3862409.5028
		Y	3105013.0619
		Z	4001942.3739
Sagara	1993.0	X	−3913435.3223
		Y	3501120.6085
		Z	3608591.3088
Chichijima	1997.0	X	−4489353.7203
		Y	3482987.4593
		Z	2887929.3978

Table 4 3D-vectors to Kashima-26m. Unit is in meters.

Point name	X	Y	Z
Tape-storage-house (KS-13)	27.033	20.626	−12.580
34m-ground (KS-14)	283.019	174.426	116.342
CB-center (KS-15)	87.495	−106.463	150.959

In April and May 1997, a local tie campaign was conducted at every VLBI site. 24-hour GPS observation was carried out between the VLBI ground marker and 3 or more GEONET points. Analysis was done by GAMIT and the results were carried over to the later adjustment.

2.1.4 Discussion

As an example of data evaluation, we compared the calculated Shintotsukawa coordinates with the latest VLBI results in 1996-1998 (Table 5). Good agreement of the two indicates that there will be no large systematic errors in the fundamental VLBI network for JGD2000.

Table 5 Comparison of JGD2000 and VLBI results (1996-1998) at Shintotsukawa VLBI station in ITRF94 at 1997.0. NEU are components of the local geodetic coordinate system.

	JGD2000	VLBI	Difference (m)		
X	−3642139.668	−3642139.659	−0.009	N	0.007
Y	2861494.750	2861494.748	−0.002	E	−0.007
Z	4370358.902	4370358.898	−0.004	U	0.001

2.2 Continuous GPS Network (GEONET)

2.2.1 History of Continuous Observation Network

The first continuous GPS observation network was constructed on the east coast of Izu peninsula to monitor the crustal deformation caused by a swarm of earthquakes off the Izu coast in 1989. In 1994, COSMOS-G2 with 110 stations began to monitor the South-Kanto and Tokai region and the nationwide Grapes network with 100 stations was also established. Both networks successfully detected coseismic and postseismic crustal deformation caused by big earthquakes in Hokkaido and the Kinki region, i.e. Hokkaido-Toho-Oki (1994, M8.1) and Hyogo-Ken Nanbu (1995, M7.2). In 1996 GSI combined COSMOS and Grapes and added 400 more stations to build a denser nationwide network called GEONET. It grew to consist of more than 950 stations in 2002 and 1,200 in 2004 with an average distance of 20 km, one of the most densely constructed continuous GPS observation networks in the world. Three analysis software packages, GIPSY, BERNESE and GAMIT/GLOBK, are available at GSI. BERNESE is used for routine crustal deformation analysis (Hatanaka et al., 2003).

2.2.2 Network and Data

In 1996-1997, 612 stations in the GEONET and 4 other continuous observation stations for orbit determination were in operation (Plate 4). Two major families of receivers, Trimble and Topcon, were used in the network. As we set the reference epoch for JGD2000 as 1997.0, data from 6 days of observation, 1996/12/27, 28, 31, 1997/1/1, 4, 5, were chosen. 595 points out of 616 with more than 5 days of data in the period were used for the calculation.

2.2.3 Reference Point for GPS and Calculation

Similar to VLBI, the reference position of the GPS survey has to be designated unambiguously. The phase center of the GPS antenna is the ideal choice but we took the base-surface of the antenna as the reference taking into account the reported errors of antenna constant (distance from the base-surface to phase center) provided by the manufacturers. The adopted constants are listed in Table 6.

GAMIT/GLOBK software (MIT&SIO, 1997 and Herring, 1997) was employed to calculate and adjust the positions of the space-geodetic network in the ITRF94. The procedure we took was as follows:

a) First, block-wise and receiver-wise daily GPS solutions were calculated by GAMIT ver.9.56.
b) Daily solution was obtained by GLOBK ver.4.12H to combine and adjust GPS solutions, VLBI and Tokyo-Taisho (see next section) data. VLBI points connected the two kinds of receiver networks.
c) Final coordinates at 1997.0 were the means of 5 or more of solution b).

Three VLBI positions were held fixed and the positions of 4 VLBI, 595 GEONET points and Tokyo-Taisho were adjusted to construct the framework of JGD2000.

Table 6 Antenna constants for GEONET

Antenna type	Constant (m)	Source
Topcon	0.087	National Geodetic Survey, USA
Trimble	0.083	
Leica	0.073	GSI, Japan

2.2.4 Results and Evaluation

The standard error of GEONET coordinates was 2 mm for horizontal and 10 mm for vertical components and the daily and mean value agree within 2 cm for horizontal and 5 cm for the vertical. In comparison with the VLBI solutions, the adjusted value agrees within 3 cm in horizontal and 6 cm in vertical.

Two fixed VLBI stations began operating after the adjustment of GEONET coordinates. We checked the JGD coordinates by comparing the VLBI and GPS solutions. The GPS solutions were obtained by observations between nearby GEONET points and the ground marker. The agreement is good enough as depicted in Table 7.

Table 7 Comparison of VLBI and GPS in ITRF94 at 1997.0

Station name	VLBI - GPS (m)			
Aira	X	0.014	N	0.010
	Y	−0.028	E	0.008
	Z	−0.007	U	−0.029
Chichijima	X	−0.035	N	−0.031
	Y	0.008	E	0.015
	Z	−0.018	U	0.021

2.2.5 Completion of the Fundamental Network

Since 1997, GEONET has kept expanding and we have tried to accommodate as many points as possible into the fundamental network for JGD2000. 356 more stations were chosen and their coordinates were calculated referenced to the pre-determined neighboring GEONET points. Thus the construction of the fundamental network for JGD2000 was completed.

2.3 Datum Origin

2.3.1 Datum Origin and Tokyo-Taisho

One special point needs to be mentioned as regards the conceptual definition of JGD2000. It is a horizontal system and based on the classical method of specifying the datum origin followed by the determination of defining parameters, its position on the reference ellipsoid and the azimuth to another point in the datum. We had to renew these parameters to be compatible with ITRF. Because the origin of the Tokyo Datum (the Origin) is situated in an environment virtually impossible to carry out GPS observation, we used the nearest (76 m from the Origin) 1st-order triangulation point, Tokyo-Taisho as a surrogate origin. Tokyo-Taisho, was established in a recovery survey to update the coordinates of triangulation points in the Kanto area including the Origin right after the Great Kanto earthquake in 1923 (Matsumura et al., 2004).

From the GPS observation on Tokyo-Taisho and angle and distance measurements between the Origin, we calculated the basic parameters for the new horizontal datum. As for the azimuth, the metal marker on the ground adjacent to the Tsukuba 32 m antenna (Plate 1) was the target point from the Origin.

2.3.2 Survey Data and Calculation

In April 1997, GPS observation on Tokyo-Taisho and surrounding GEONET points was carried out. The position of Tokyo-Taisho was determined in ITRF94 in the framework adjustment (see 3.3 for the result).

Surveys between Tokyo-Taisho and the Origin were done in 1984, 1987, 1999 and 2000. Angles, distances, leveling and GPS measurements were included.

The survey results are as follows:

Distance on the ellipsoid: 76.656 m
Relative height: +1.374 m
Angle from Sendagaya (1st-order) to Origin:
344° 01′ 20.1″

The position of the Origin was calculated using the above survey results with Tokyo-Taisho fixed.

To calculate the azimuth, the position of the Tsukuba antenna marker must be known. GPS observation was carried out on the marker and 2 GEONET points (92110, 96062) at GSI, Tsukuba. Analysis was done by GPSurvey (WAVE ver2.35) with broadcast ephemeris and 6 days of results were averaged to get the following coordinates of the marker.

On the GRS80 ellipsoid:

Latitude:	36° 06′ 11.5078″
Longitude:	140° 05′ 20.6789″
Height:	25.48 m
Ellipsoidal height:	65.590 m

Or in Cartesian coordinates (ITRF94, m):

X:	−3957414.089
Y:	3310193.827
Z:	3737488.061

2.3.3 Results

The coordinates of the Origin were calculated as follows.

In geographical coordinates (ITRF94, GRS80 ellipsoid)

Latitude:	35° 39′ 29.1572″
Longitude:	139° 44′ 28.8759″
Height:	26.778 m

Ellipsoidal height: 63.34 m

Or in Cartesian coordinates (ITRF94, m):

X: −3959340.0897
Y: 3352864.5405
Z: 3697471.4746

The above values were checked with the GAMIT solution and the differences were 0.0001 arcsec for the horizontal and 0.045 cm for the height component.

GSI's routine procedure was adopted for the azimuth calculation and the result was 32° 20′ 4.756″.

2.3.4 Evaluation and Checking of the Results

The position of Tokyo-Taisho was checked with GPS surveys from neighboring GEONET points, Adachi and Nerima. The differences in Cartesian coordinates were as follows:

	X	Y	Z (m)
From Adachi:	−0.003	0.001	0.012
From Nerima:	−0.003	0.009	0.019

The position of the Tsukuba antenna marker was checked by a GAMIT solution using precise orbit information. The differences were 0.0001 arcsec for the horizontal and 0.045 m for the height component.

3. Horizontal Geodetic Coordinates 2000 of 1st- to 3rd-order Triangulation Points

Here we review the calculation procedure of Geodetic Coordinates 2000 of the 1st- to 3rd-order triangulation points. These 38,000 points had been serving as indispensable control points that realized the previous Tokyo Datum, and they continue to be important densification points of JGD2000, providing stable adjacent control points to public surveys especially for users of total station instruments. Since the coordinates of these points have been re-adjusted using the most recent geodetic survey data available, actually ranging from classical triangulation, modern EDM trilateration, and more recent GPS surveying data, a brief history of geodetic surveys at these points is reviewed in Section 3.1.

Section 3.2 describes a general strategy of network adjustments of these data, as well as giving some notes why the heights of triangulation points have not been updated this time.

Although the final reference frame of JGD2000 is ITRF94, the actual network adjustments are conducted on an intermediate reference frame named the Tokyo97 Datum. Section 3.3 explains the definition and justification of the Tokyo97 Datum, along with a transformation procedure from ITRF94 to the Tokyo97 Datum. This transformation is necessary to obtain the coordinates of the GEONET stations that are fixed for the network adjustments of triangulation points.

Section 3.4 is the main part of this chapter, explaining the data, method and results of the network adjustments of the 1st- to 3rd-order triangulation points. Depending on the survey network, data type, and area, hierarchical adjustments at 3 or 4 levels are done by either a three dimensional or horizontal network adjustment, fixing the coordinates of the upper networks.

Section 3.5 explains the procedure for transforming the adjusted coordinates of the 1st- to 3rd-order control points from Tokyo97 Datum back to ITRF94. Since we need the ellipsoidal heights of triangulation points for this transformation, some care should be taken.

3.1 History of Geodetic Surveys at Triangulation Points

Table 8 shows the current number of triangulation points in Japan. As their name implies, the 1st- to 3rd-order triangulation points were initially surveyed by the triangulation method with theodolites, along with baseline measurements with invar steel rods mainly in the Meiji era (1868-1911). They were conducted by the Government of Japan, which was eager for modern topographic maps for national development.

Table 8 Numbers of triangulation points as of 2002. The 4th-order triangulation points are discussed in Chapter 4.

Triangulation points	Number	Sum total	Mean distance
1st order	973	973	25 km
2nd order	5,056	6,029	8 km
3rd order	32,723	38,752	4 km
4th order	63,806	102,558	1.5 km

The triangulation network at that time had a three level hierarchy. The 1st-order triangulation network (surveyed in the period 1882-1913) defined the framework of the Tokyo Datum of about 25 km spacing. The 2ndorder triangulation network (surveyed in 1883-1917) and the 3rd-order triangulation network (surveyed in 1883-1920) densified the Tokyo Datum referring to the coordinates of upper order triangulation points. Using the geodetic network, productions of 1 to 50,000 scale topographic maps started in 1895, and most of Japan was covered with maps of this scale by 1924.

Although the initial mission of the triangulation network was successfully completed, that was not the end of the triangulation surveys. Since the Japanese islands are located in a tectonically active region where four tectonic plates (i.e. the Pacific, North American, Eurasian, and the Philippine Sea Plates) meet, they suffer from constant and episodic crustal deformations associated with plate motions, earthquakes and volcanic eruptions. If the accumulated deformations become large enough, the discrepancy between the published coordinates of control points and their actual positions will cause serious inconsistency in follow-on surveys, requiring re-surveys and updates of the coordinates of the affected control points.

For example, the part of the triangulation network in Shikoku island and the Kii peninsula in western Japan was heavily distorted after the Nankai Earthquake (M 8.0) of December 21, 1946. To recover these distortions, GSI conducted recovery triangulation surveys at 117 1st-order triangulation points during 1947-1950, and at 1,797 2nd- and 3rd-order triangulation points during 1948-1952. Based on the results, updates about 4,000 of the 1st- to 3rd-order triangulation points were completed in 1956. These surveys vividly illustrate the nature of this earthquake, demonstrating the importance of geodetic surveying to crustal deformation studies. Actually, motivated by the success of the Nankai Earthquake Recovery Survey, GSI started re-survey of the whole of the 1st-order triangulation points from 1953, completing this 2nd national triangulation survey by 1967. The obtained data revealed the horizontal crustal deformation of Japan in these 50 years.

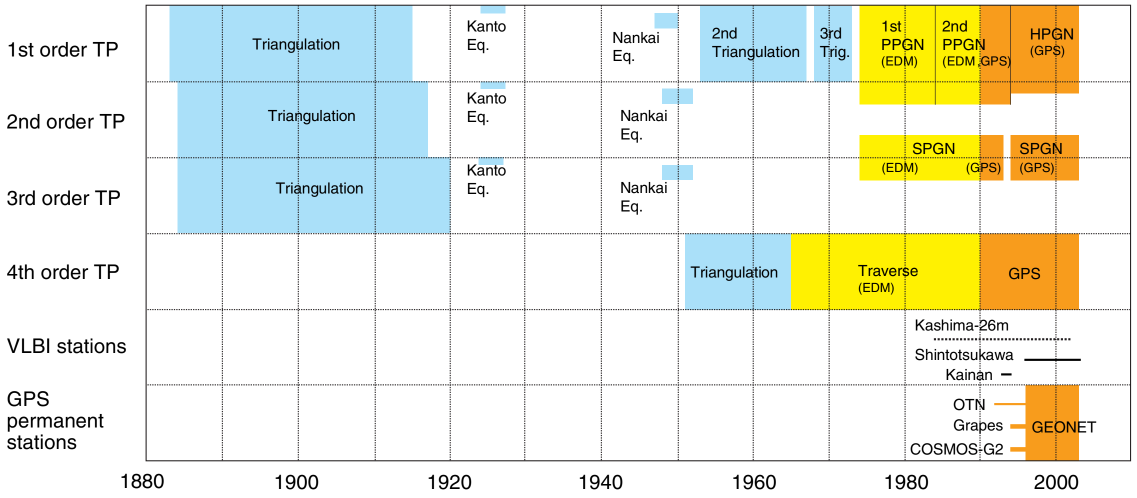
The introduction of EDM in the 1970s enabled more precise and efficient surveys than the triangulation method. GSI launched a new survey project using EDM in 1974, i.e. the Primary Precise Geodetic Network (PPGN) survey to cover the 1st- and 2nd-order triangulation points, and the Secondary Precise Geodetic Network (SPGN) survey to cover the 3rd-order triangulation points (Plate 5). The first cycle of PPGN surveys was completed in 1984, yielding valuable crustal deformation data at most of the 1st-order triangulation points, and about half of the 2nd-order triangulation points. The SPGN surveys were conducted from the areas that needed urgent re-survey with urban development or large crustal deformation, covering approximately one tenth of the 3rd-order triangulation points by 1990.

The next revolution in surveying techniques came with GPS in the 1980s. GSI introduced four GPS receivers for an experimental purpose in 1987. GPS was applied to a part of the second cycle of PPGN surveys in the early 1990s after the confirmation of its efficiency and accuracy. Since then, GSI has utilized GPS in many fields of surveying and mapping.

Continuous GPS measurement at four fixed stations in Japan was initiated in 1990 for regional orbit tracking. Crustal deformation monitoring by 110 permanent GPS stations (COSMOS-G2) in the Tokai and South Kanto areas started in 1994. A nationwide GPS array with 100 GPS stations (Grapes) was established in 1994. In 1996, these systems were expanded and integrated into the GPS Earth Observation Network System (GEONET) of 640 GPS stations. The GEONET has grown in time and currently holds over 1,200 permanent GPS stations, providing valuable data on crustal deformation in Japan.

Using GEONET as given points, a new GPS survey project at selected 1st- and 2nd-order triangulation points started in 1994. This is the Highly Precise Geodetic Network (HPGN) survey, replacing the previous PPGN survey.

Fig.2 summarizes the history of major geodetic surveys in Japan. In sum, the 1st- to 3rd-order triangulation points were re-surveyed using the latest technologies available in each decade, such as EDM in the 1970s and 1980s, and GPS after the 1990s. Without these continued efforts of geodetic surveying, re-adjustment of coordinates of these triangulation points would not have been possible in time.



TP: Triangulation Point
Grapes: GPS Regional Array for Physical Earth Science
OTN: Orbit Tracking Network
COSMOS -G2: Continuous Strain Monitoring Observation System by GPS at GSI

PPGN: Primary Precise Geodetic Network
SPGN: Secondary Precise Geodetic Network
HPGN: Highly Precise Geodetic Network

Fig. 2 Major Geodetic Surveys of Horizontal Control Points in Japan

3.2 General Strategy

3.2.1 Scenario of Network Adjustment

We constructed the new geocentric reference frame JGD2000 using space geodetic techniques to resolve the internal distortions and datum shift of the previous Tokyo Datum. We have seen how the framework of JGD2000 is realized at VLBI and GPS permanent stations in Chapter 2. This was a rather straightforward calculation because the latest three dimensional space geodetic data are available. The situation is almost the same for the triangulation points that have been measured by EDM or GPS in the 1980s and 1990s. However, for the vast majority of the 2nd- and 3rd-order triangulation points, the most recent data are the horizontal angles before 1950 as described in Section 3.1. Can we use those classical data from several decades ago ?

To answer this question, let’s examine the major error sources of the previous Tokyo Datum, i.e.

1) Calculation errors in network adjustments; this includes errors caused by a manual adjustment by the block about 100 years ago,
2) Neglect of geoidal heights and deflections of the vertical when observations were projected on the reference ellipsoid; such information was not available about 100 years ago,
3) Observation errors in horizontal angle measurements, and
4) Accumulation of crustal deformation due to plate motions, earthquakes, and volcanic eruptions.

It is possible to minimize the errors associated with 1) and 2) if we perform large scale network adjustments of triangulation data on computers using the latest geoid model. Observation errors 3) are inevitable, but the quality of Japanese triangulation data was high, judging from the average of the standard errors of one horizontal angle observation being 0.66 arcsec (GSI, 1970). Errors from 4) are difficult to model because we only have one epoch of observations from about 100 years ago. However, it is expected that distortions can be reduced by fixing the latest coordinates of the space geodetic network or the upper triangulation points.

After the adjustment calculation, we checked the residuals of the classical observations and excluded problematical points whose residuals of horizontal angle or distance are larger than 10 arcsec or 10 cm, respectively. Excluded points come to about 0.7% of the 1st- to 3rd-order control points, confirming the validity of the scenario of using classical data to fill in gaps of the space geodetic points and upper triangulation points.

3.2.2 Heights of Triangulation Points

This section gives some notes on the heights of triangulation points which were not updated in the recent release of Geodetic Coordinates 2000.

The current heights of the 1st- to 3rd-order triangulation points were determined from the 3rd-order triangulation surveys during 1884-1920 mainly by an indirect leveling that observed elevation angles between adjacent points. Some points in flat areas were directly connected to the national leveling network by leveling surveys (GSI, 1970). In broad terms, the nominal precision of such heights is about 20 cm. Except for local updates after giant earthquakes, most of the heights have not been updated since their establishment about 100 years ago.

As well known, the purpose of the triangulation network is to provide horizontal coordinates, i.e. longitudes and latitudes for geodetic control. However, in classical Geodesy, we need ellipsoidal heights to project distance observations at the surface of the Earth on a reference ellipsoid. About 100 years ago, heights above the sea-level of triangulation points were used instead of ellipsoidal heights neglecting geoid undulation.

In the planning stage of JGD2000, revision of heights of triangulation points was on the agenda, but we came to the conclusion that the priority of the revision of heights is not the highest considering the following aspects.

1) The Tokyo Datum is a compound coordinate system where longitudes and latitudes are realized by triangulation points, and heights by leveling points.
2) Although the definition of horizontal coordinates has been completely changed to adopt a geocentric system, that of vertical coordinates remains the same (Imakiire and Hakoiwa, 2004).

However, the revision of heights of the nationwide triangulation points is a task to be accomplished in the near future.

3.3 Tokyo97 Datum

3.3.1 What is Tokyo97 Datum ?

As stated, we constructed a new geocentric reference frame using space geodetic techniques to resolve the datum shift and internal distortions of the previous Tokyo Datum. Although the former can be handled by a simple datum transformation with 3 or 7 parameters (see Seeber, 2003, for example), the latter requires more a sophisticated approach to handle the complicated internal distortions of Tokyo Datum.

In an early effort to establish a distortion-free geodetic reference frame, modern surveying data at about 3,000 primary control points (i.e. the 1st- and part of the 2nd-order triangulation points covered by PPGN surveys) are adjusted with domestic VLBI solutions, introducing an experimental new datum, the Tsukuba Datum of 1992 (Tobita, 1994). Similarly, we defined a new datum, Tokyo97, that has the same ellipsoid (i.e. Bessel ellipsoid) and origin as the Tokyo Datum, and with the same orientation as ITRF94 (Tobita, 1997a). Using the Tokyo97 Datum as an intermediate working datum to relate the Tokyo Datum and ITRF94, we can simplify the transformation into two parts, i.e. 1) mathematical datum shifts between ITRF94 and Tokyo97, 2) local corrections of network distortions between Tokyo97 and the Tokyo Datum. All the results of network adjustments on Tokyo97 are to be transformed to a geocentric system. By definition, geoidal height is zero at the Origin of Tokyo97, i.e. the 1st order triangulation point Tokyo-Taisho.

3.3.2 Transformation from ITRF94 to Tokyo97

Transformation parameters between ITRF94 and Tokyo97 are obtained from the differences of Cartesian coordinates of Tokyo-Taisho in ITRF94 and Tokyo97.

ITRF94 coordinates at 1997.0 epoch (i.e. JGD2000) of Tokyo-Taisho are derived from the GLOBK adjustment of GPS survey data with Kashima VLBI station. They are

$$X = -3{,}959{,}397.030 \text{ m},$$
$$Y = 3{,}352{,}807.492 \text{ m},$$
$$Z = 3{,}697{,}450.922 \text{ m}$$

or

$$B = 35^\circ\ 39'\ 28.3686'',$$
$$L = 139^\circ\ 44'\ 31.7662'',$$
$$h = 61.959 \text{ m}$$

where B, L, h denote latitude, longitude, and ellipsoidal height associated with a GRS80 ellipsoid, respectively. The conversion formulae between X, Y, Z and B, L, h can be found in a geodesy textbook (see Seeber, 2003 for example). The following semi-major axis a, and flattening f of GRS80 ellipsoid are used of course.

$$a = 6{,}378{,}137 \text{ m},$$

$f = 1/298.257222101$.

By definition, the Tokyo97 coordinates of Tokyo-Taisho are set to be equal to those of the Tokyo Datum, i.e.

$$B = 35° 39' 16.7000'',$$
$$L = 139° 44' 43.3980'',$$
$$h = 25.404 \text{ m},$$

or

$$X = -3{,}959{,}250.616 \text{ m},$$
$$Y = 3{,}352{,}300.155 \text{ m},$$
$$Z = 3{,}696{,}770.415 \text{ m}.$$

where B, L, h denote the latitude, longitude, and ellipsoidal height associated with the Tokyo97 (Bessel) ellipsoid, respectively. The following semi-major axis a, and flattening f of the Tokyo97 ellipsoid are used in this conversion.

$$a = 6{,}377{,}397.155 \text{ m},$$
$$f = 1/299.152813.$$

By differencing these Cartesian coordinates X, Y, Z of the same point in both systems, the following transformation parameters are obtained. The unit is meters.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{Tokyo97} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{ITRF94} + \begin{pmatrix} +146.414 \\ -507.337 \\ -680.507 \end{pmatrix}.$$

This transformation causes changes in latitude and longitude of about 7 through 14 arcsec and –15 through –8 arcsec, respectively.

Using these parameters, the coordinates of the GEONET stations are transformed to the Tokyo97 datum before the network adjustments of triangulation points.

3.3.3 Justification for using Tokyo97 Datum

The geometrical result of a three dimensional network adjustment of GPS vectors is independent of the choice of a reference ellipsoid. However, in the case of a horizontal network adjustment of distance and angle observations, the result might have weak dependence on the choice of an ellipsoid for the following reasons.

1) Reductions of distance observations to the reference ellipsoid use ellipsoidal heights that are obtained from heights above the sea-level plus model geoidal heights (See Section 3.4.2). A difference of ellipsoid could cause difference in the argument of a geoid model, giving some difference on the projected distance.
2) Deflections of the vertical are neglected in the reduction of horizontal angle observations. Note that the average deflections of the verticals on the Tokyo97 ellipsoid are about 10 arcsec in both north-south and east-west components, whereas those on ITRF94 are close to zero.

To evaluate the effect of 1), a test calculation for about 3,000 of the primary control points was conducted on the GRS80 ellipsoid, confirming that the coordinate difference with that on the Tokyo97 ellipsoid is below 2 mm at 97% of all the points, and that the maximum discrepancy is 4 mm.

To evaluate the effect of 2), test calculations for the 3rd-order Triangulation Network were performed both in the Tokyo97 Datum and ITRF94 for several areas in Japan. Horizontal angle observations are used without correcting the deflections of the verticals. The differences between Tokyo97 and ITRF97 solutions are below 3 cm for most of the cases, and smaller than 5 cm even at mountain areas with a large height difference between triangulation points. This justifies the network adjustments on the Tokyo97 Datum.

3.4 Adjustment of 1st- to 3rd-order Triangulation Points

3.4.1 Data and Procedure

Fig.3 shows a schematic flow of the hierarchical network adjustments of the 1st- to 3rd-order triangulation points on the Tokyo97 Datum. The calculation is done in the following order:

1) Adjustment of Highly Precise Geodetic Network (HPGN) with respect to GEONET,
2) Adjustment of Primary Precise Geodetic Network (PPGN) with respect to HPGN and GEONET,
3) Adjustment of Secondary Precise Geodetic Network (SPGN) with respect to GEONET / HPGN, and
4) Adjustment of Third-order Triangulation Network (TTN) and Earthquake Recovery (ER) surveys with respect to HPGN / PPGN / SPGN.

Table 9 shows the survey data used for these adjustments. The most recent data available at each point are used. Explanations on each survey project already appeared in Section 3.1. Additional local tie surveys are conducted to connect selected points of PPGN, SPGN, ER, and TTN to GEONET by GPS surveying in 1995-1998. Actually, HPGN surveys can be viewed as local tie surveys to GEONET.

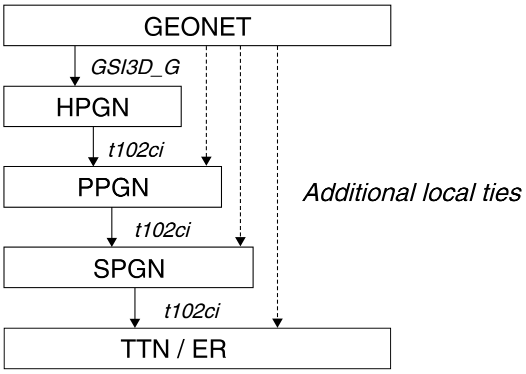


Fig. 3 Sequence of network adjustments. The upper level of the network is fixed in each network adjustment. *GSI3D_G* and *t102ci* are the programs used for the adjustments (See Section 3.4.3).

Table 9 Survey data used for the network adjustments of the 1-st to 3rd-order triangulation points

No.	Geodetic Survey Projects	Observation Period	Target / Area	Method	Number of surveyed / adjusted	Notes
1	Highly Precise Geodetic Network (HPGN) Surveys	1994-2003	Selected 1st and 2nd order TP* + GEONET	GPS surveying w.r.t.** GEONET	493	Data from 1994 to 1998 are adjusted.
2	Local Tie Surveys to GEONET	1995-1998	Part of PPGN, SPGN, and ER for connection to GEONET	GPS surveying w.r.t. GEONET	401	All data used as local ties.
3	Primary Precise Geodetic Network (PPGN) Surveys	1973-1993	Selected 1st and 2nd order TP	Trilatelation by EDM or GPS	2,446	
4	Secondary Precise Geodetic Network (SPGN) Surveys	1973-2003	Selected 2nd and 3rd order TP of special interests	Trilatelation, Traverse, and GPS surveying	3,069	Data to 1998 are adjusted.
5	Earthquake Recovery (ER) Surveys	1925-1972	TPs in areas of large crustal deformation due to large earthquakes	Triangulation	2,657	
6	Third-order Triangulation Network (TTN) Surveys	1884-1920	All 3rd order TP	Triangulation	***51,970	

* TP: Triangulation Point
** w.r.t.: with respect to
*** Includes overlap of the same point in different survey networks

3.4.2 Reduction of Observed Distance to Ellipsoid

Before the adjustment of the EDM observed distance of PPGN and SPGN surveys, reduction to the reference ellipsoid is done. Let the measured distance be s and the distance projected on the ellipsoid be S, then distance reduction is given as

$$d\,(S-s) = -\frac{s}{R}dH - \frac{h}{s}dh,$$

where h is the relative height, R is the radius of curvature, and dh and dH are errors of relative height and mean height, respectively.

To keep the first term below 1 cm for a typical PPGN survey ($s \sim 20$ km), dH should be below 3.2 m. This condition holds, if we use a numerical geoid model "Geoid of Japan 96" (JGEOID96), whose precision is better than 20 cm (See Section 3.7) , and heights of triangulation points whose errors do not exceed 1 m in the worst case.

The second term can be large for short baselines with large relative height. Therefore, the PPGN survey procedure mandates re-measurement of relative height if $h / s > 1/10$. Since dh is expected to be better than 30 cm, the second term will not exceed 3 cm, i.e. below the typical precision of EDM measurement.

The past database of PPGN and SPGN surveys contains distances that are reduced to the geoid surface using heights of triangulation points which are measured from the mean sea-level. Therefore, we made reductions of those data to the reference ellipsoid in the following way.

1) Convert distance S_g on the geoid to spatial distance D between triangulation points by

$$D = \sqrt{4(R+H_1)(R+H_2)\sin^2\left(\frac{S_g}{2R}\right) + (H_2-H_1)^2},$$

$$R = \frac{NM}{N\cos^2\alpha + M\sin^2\alpha},$$

$$\alpha = \frac{1}{2}(\alpha_{12} + \alpha_{21}),$$

where H_1 and H_2 are the heights of triangulation points, and R is the ellipsoidal radius of curvature in the azimuth α, N is the radius of curvature in the prime vertical, M is the radius of curvature in the meridian, α_{12} is the azimuth of Point 2 at Point 1, and α_{21} is the back azimuth.

2) Refer to JGEOID96 model, adding the height of triangulation point to yield ellipsoidal height h_1 and h_2.

3) Project the spatial distance D on the ellipsoid to obtain geodesic distance S by

$$S = 2R\arcsin\left(\frac{1}{2}\sqrt{\frac{D^2-(h_2-h_1)^2}{(R+h_1)(R+h_2)}}\right).$$

3.4.3 Methods of Adjustments

The adjustment of survey data at triangulation points is conducted using 1) a three dimensional adjustment program *GSI3D_G* for GPS observations, and 2) a horizontal network adjustment program *t102ci* for distance and direction observations. These are in-house programs developed by GSI. Here follow their brief explanations.

GSI3D_G

1) The observation equation is

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} \delta X_j \\ \delta Y_j \\ \delta Z_j \end{bmatrix} - \begin{bmatrix} \delta X_i \\ \delta Y_i \\ \delta Z_i \end{bmatrix} + \begin{bmatrix} \Delta X_{ij} \\ \Delta Y_{ij} \\ \Delta Z_{ij} \end{bmatrix} - \begin{bmatrix} \Delta X_{ob} \\ \Delta Y_{ob} \\ \Delta Z_{ob} \end{bmatrix},$$

where X, Y, Z are geocentric Cartesian coordinates, V_x, V_y, V_z are residuals, δX, δY, δZ are corrections of coordinates at adjusted points, ΔX, ΔY, ΔZ are calculated baseline vector components, and ΔX_{ob}, ΔY_{ob}, ΔZ_{ob} are baseline vectors obtained from GPS observations.

2) The weight matrix is

$$\mathbf{P} = \Sigma_{\Delta \mathrm{X}, \Delta \mathrm{Y}, \Delta \mathrm{Z}}^{-1} = \begin{bmatrix} \sigma_{\Delta X \Delta X} & \sigma_{\Delta X \Delta Y} & \sigma_{\Delta X \Delta Z} \\ \sigma_{\Delta Y \Delta X} & \sigma_{\Delta Y \Delta Y} & \sigma_{\Delta Y \Delta Z} \\ \sigma_{\Delta Z \Delta X} & \sigma_{\Delta Z \Delta Y} & \sigma_{\Delta Z \Delta Z} \end{bmatrix}^{-1},$$

where σ_{ij} is the covariance between the i-th and j-th components of the baseline vectors. In the case of PPGN surveys, we use the following fixed weight. The unit is meters.

$$\mathbf{P} = \begin{bmatrix} 0.005^2 & 0 & 0 \\ 0 & 0.005^2 & 0 \\ 0 & 0 & 0.005^2 \end{bmatrix}^{-1}.$$

3) The standard deviation of observation of a unit weight is

$$M = \sqrt{\frac{\mathbf{V}^t \mathbf{P} \mathbf{V}}{3(m-n)}},$$

where $\mathbf{V}$ is the residual vector, m is the number of baselines, and n is the number of unknown points.

t102ci

1) Observation equations for distance s and direction T are

$$v(s_{12}) = \frac{v(s_{12})}{S'_{12}} \rho$$

$$= -a_{12} d\lambda_1 - b_{12} \delta\phi_1 + a_{21} d\lambda_2 + c_{12} \delta\phi_2 - \frac{S_{12} - S'_{12}}{S'_{12}} \rho,$$

$$v(T_{12}) = -\Delta Z_1 - d_{12} d\lambda_1 + e_{12} \delta\phi_1 + d_{21} d\lambda_2 - f_{12} \delta\phi_2 - l_{12},$$

where

$$a_{12} = \frac{N \cos\phi \sin\alpha}{S'_{12} \cos\phi_1},$$

$$a_{21} = \frac{N \cos\phi \sin\alpha}{S'_{12} \cos\phi_2},$$

$$b_{12} = \frac{M}{S'_{12}} \cos\alpha + \frac{N}{2S'_{12}} \sin\phi \sin\alpha \, \Delta\lambda,$$

$$c_{12} = \frac{M}{S'_{12}} \cos\alpha - \frac{N}{2S'_{12}} \sin\phi \sin\alpha \, \Delta\lambda,$$

$$d_{12} = \frac{\cos\phi}{\cos\phi_1} \left(\frac{N}{S'_{12}} \cos\alpha - \frac{\tan\phi}{2} \right),$$

$$d_{21} = \frac{\cos\phi}{\cos\phi_2} \left(\frac{N}{S'_{12}} \cos\alpha - \frac{\tan\phi}{2} \right),$$

$$e_{12} = \frac{M}{S'_{12}} \sin\alpha - \frac{N}{2S'_{12}} \sin\phi \cos\alpha \, \Delta\lambda,$$

$$f_{12} = \frac{M}{S'_{12}} \sin\alpha + \frac{N}{2S'_{12}} \sin\phi \cos\alpha \, \Delta\lambda,$$

$$d\lambda_1 = \cos\phi_1 \, \delta\lambda_1, \quad d\lambda_2 = \cos\phi_2 \, \delta\lambda_2,$$

$$l_{12} = Z'_1 + U_{12} - A'_{12},$$

$$\alpha = \frac{1}{2} (\alpha_{12} + \alpha_{21}),$$

$$\phi = \frac{1}{2} (\phi_1 + \phi_2),$$

$$\Delta\lambda = \lambda_2 - \lambda_1,$$

$$\Phi_1 = \phi_1 + \delta\phi_1, \quad \Phi_2 = \phi_2 + \delta\phi_2,$$

$$\Lambda_1 = \lambda_1 + \delta\lambda_1, \quad \Lambda_2 = \lambda_2 + \delta\lambda_2,$$

Φ_i, Λ_i is adjusted latitude and longitude of point i, ϕ_i, λ_i are approximate latitude and longitude, $\delta\phi_i$, $\delta\lambda_i$ are corrections of latitude and longitude, S'_{12} is approximate geodesic distance between Point 1 and 2, S_{12} is observed distance reduced on the ellipsoid, ΔZ_1 is orientation unknown, Z'_1 is the zero angle (i.e. computed azimuth of the zero meridian at the Point 1), U_{12} is observed direction of Point 2 at Point

1, A'_{12} is approximate azimuth of Point 2 at Point 1, M is the curvature in the meridian, N is the curvature in the prime vertical, α_{12} is approximate azimuth of Point 2 at Point 1, and α_{21} is approximate azimuth of Point 1 at Point 2 ±180°, and ρ is arcsec of 1 radian (=206,265).

2) Weights of distance P_s and direction P_t are

$$P_s = \frac{m_t^2 S^2}{(m_s^2 + \gamma^2 S^2)\rho^2}, \quad P_t = \frac{N_t}{N}$$

where S is an observed distance, $m_s = 0.5$ cm, $\gamma = 2 \cdot 10^{-6}$; m_t=1.0 arcsec, N=6, N_t=6 for PPGN; m_t= 1.4 arcsec, N=3, N_t=3 for SPGN.

3) The standard deviation of observation of a unit weight is

$$m_0 = \sqrt{\frac{\sum_{i=1}^{m} P_i v_i^2}{m - r}},$$

where m is the number of observation equations, and r is the number of unknown parameters.

3.4.4 Results

1) HPGN

HPGN is connected by GPS surveys with respect to GEONET at the 1st- and selected 2nd-order triangulation points. Baseline vectors from GAMIT / GLOBK solutions at each block (typically includes 25 triangulation points with 8 GEONET stations) are adjusted by *GSI3D_G*., yielding coordinates of 493 HPGN points distributed all over Japan. The consistency of GEONET coordinates at each block is confirmed to be better than 1 cm.

2) PPGN

PPGN is connected by trilateration surveys at 1st- and selected 2nd-order triangulation points. Coordinates of 2,467 PPGN points are adjusted simultaneously by *t102ci*, fixing the coordinates of 522 triangulation points that are connected to GEONET by HPGN or additional local tie surveys (Fig.4). The standard deviation of observation of a unit weight (m_0) is 1.05 arcsec, and the precision of relative horizontal positions between neighboring points is about 3 cm for 8 km baselines and 5 cm for 20 km baselines. Fig. 5 is the result of the adjustment, showing horizontal displacement vectors between the Tokyo97 Datum and the Tokyo Datum. The displacements reach 8 m in North Hokkaido, 5 m in Chugoku district, 4 m in Western Shikoku, and 3 m in South Kyushu, showing the complicated distortion of the previous Tokyo Datum.

3) SPGN

SPGN is connected by regional trilateration or GPS surveys at triangulation points. Trilateration data are adjusted by *t102ci* for each block (typically 50 unknown and 7 fixed points), yielding coordinates of 2,516 points with m_0 mostly below 3 arcsec. GPS data are adjusted by *GSI3D_G*, yielding coordinates of 495 points.

4) TTN

TTN is connected by triangulation surveys, partly modified by ER surveys. Points are overlapped with neighboring networks. ER survey data such as those after the Great Kanto earthquake in 1923 and the Nankai earthquake in 1946 are adjusted by *t102ci* for each area affected by the earthquakes to yield coordinates of 2,657 points in total. TTN survey data are adjusted by the prefecture (except for Hokkaido and Nagano prefecture which are divided into 5 and 2 blocks) to yield coordinates of 51,890 points with 6,592 fixed stations in total. Most m_0 are below 3 arcsec.

3.5 Transformation from Tokyo97 to JGD2000

Since the network adjustments of triangulation points were conducted on the Tokyo97 Datum, the adjusted coordinates should be transformed back to JGD2000. This may look like a simple transformation with the three parameters obtained at the Origin of Tokyo97 Datum / JGD2000 (See Section 3.3.2), but the actual calculations are a little complicated because we need ellipsoidal heights in the Tokyo97 Datum for precise three dimensional transformation.

For triangulation points whose coordinates are obtained by three dimensional network adjustment of GPS data (i.e. 1st to 3rd-order triangulation points that are occupied by GPS antennas), we can use their ellipsoidal heights directly for this transformation. Those points sum up to about 1,400.

However, for the rest of the 1st to 3rd-order triangulation points, i.e. the about 37,000 non-GPS triangulation points, we do not have any newly-adjusted

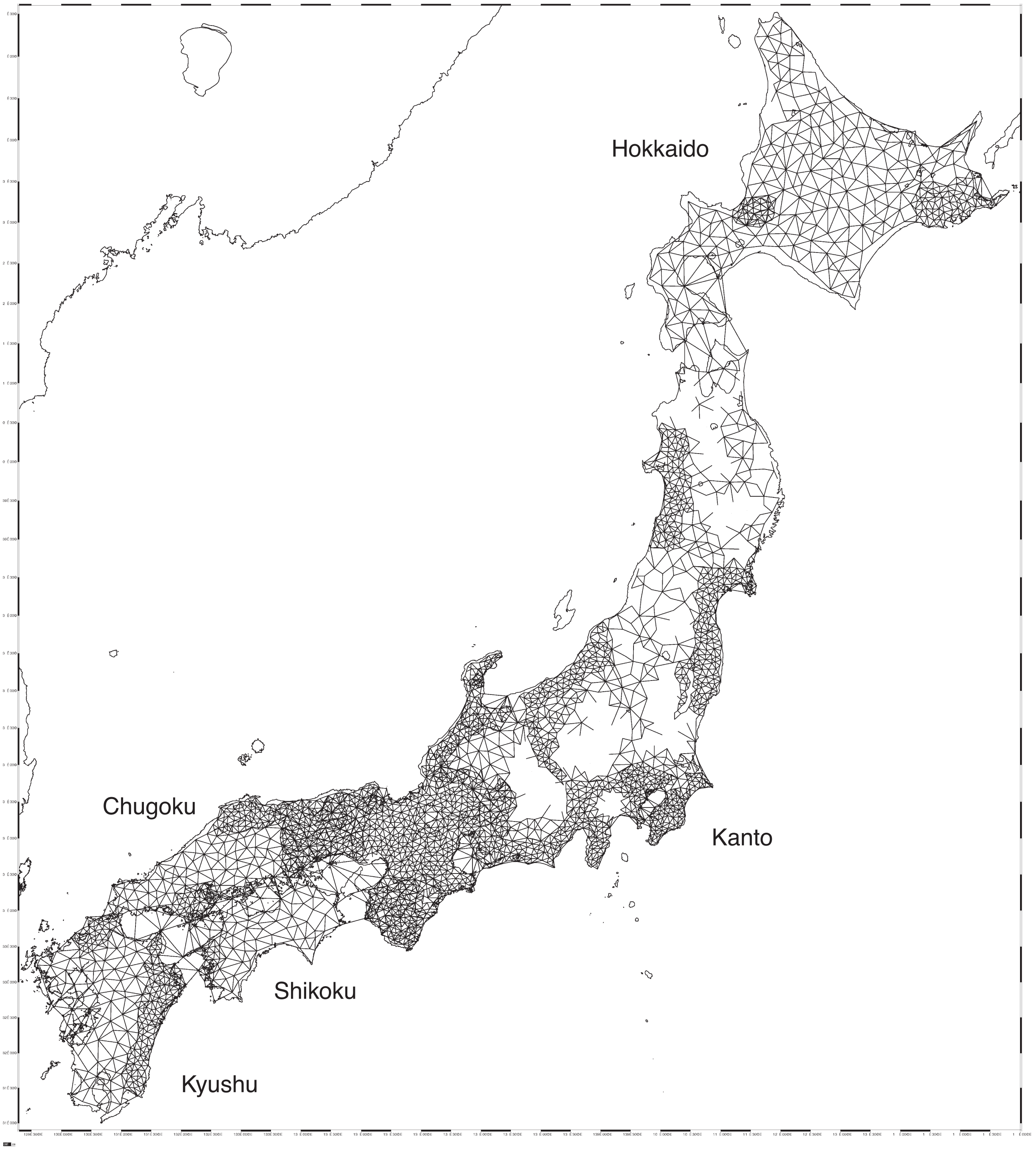


Fig. 4 The network adjustment of the Primary Precise Geodetic Network (PPGN). There are 522 fixed points and 2,467 adjusted ones.

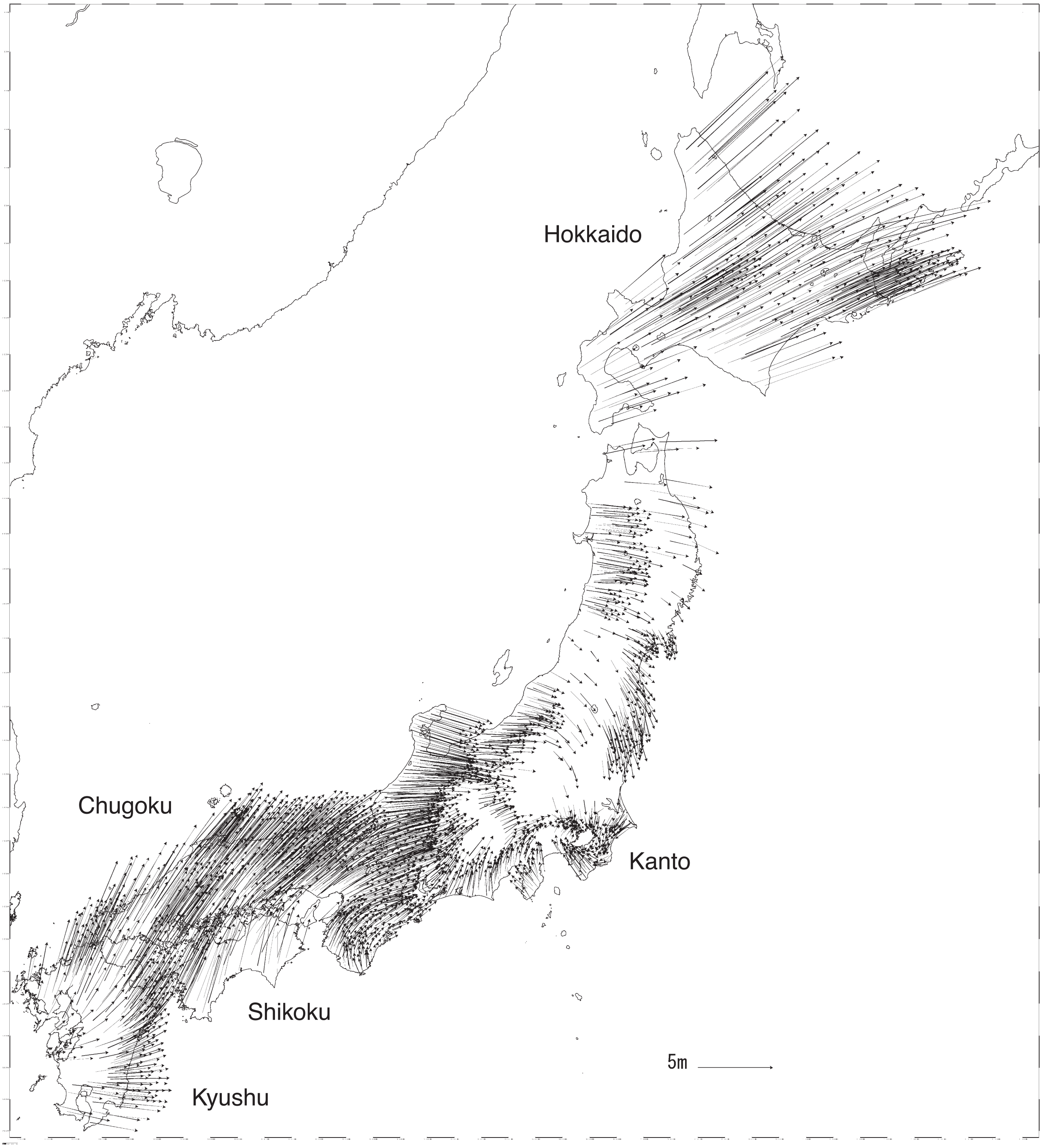


Fig. 5 Horizontal displacement vectors between the Tokyo97 Datum and the Tokyo Datum at 2,467 primary control points (all of 1st-order triangulation points and selected 2nd-order triangulation points). Displacement vectors are defined as $B_{Tokyo97}$ - B_{Tokyo} and $L_{Tokyo97}$ - L_{Tokyo}. These represent the internal distortions of the Tokyo Datum and have been used as the input to obtain local transformation parameters.

ellipsoidal heights because only longitudes and latitudes are estimated by the horizontal network adjustments explained in the previous chapters. Recall that the update of heights of triangulation points is outside the target of the JGD2000 project.

Of course, those triangulation points have heights above the geoid, that were measured mainly by indirect leveling surveys connecting the leveling network of Japan. As is well known, an ellipsoidal height He is obtained by adding an orthometric height Ho and a geoidal height Hg, i.e. $He = Ho + Hg$.

In 1996, GSI published a numerical geoid model, "Geoid of Japan 96" (JGEOID96), that gives geoidal heights above the WGS-84 ellipsoid at any WGS-84 coordinates around Japan. This model is created by the integration of gravimetric geoid and GPS/Leveling survey data by the least squares collocation (Kuroda et al., 1997). At the start of calculation of Geodetic Coordinates 2000, JGEOID96 was the most reliable model, whose precision (RMS) was considered to be about 7 cm in flat lands and 20 cm in mountains. As described before, this model was used for obtaining the approximate ellipsoidal heights of triangulation points that are necessary for the reduction of EDM-observed lengths to the reference ellipsoid, and for the correction of such reduction that had been done using heights above the geoid in the past.

However, GSI was in time to release a more accurate geoid model by March 2001. This new model named "Geoid of Japan 2000" (GSIGEO2000) is the update of the previous model with more gravimetric and GPS/Leveling data and refined analysis methods, and is consistent and refers to JGD2000. The formal error of the least squares collocation is about 4.0 cm (Nakagawa et al., 2002).

To adopt the latest geoid model for coordinate transformation of non-GPS triangulation points from Tokyo97 to JGD2000, the following procedure was used for actual calculations. Suppose a triangulation point has the newly-adjusted latitude $B_{Tokyo97}$ and longitude $L_{Tokyo97}$, with the original height Ho. Note that Ho is measured from the geoid, and is independent of the choice of a reference ellipsoid.

1) Obtain the geoidal height above the Bessel ellipsoid of Tokyo97 using JGEOID96.

   This is tricky because JGEOID96 refers to the WGS-84 ellipsoid. However, the following simple algorithm is confirmed to have enough accuracy for the conversion between nearly-aligned ellipsoids, and is implemented in a computer code named "jgeoidtrn97" (Tobita, 1997b).

   a) Transform the coordinates of a point on the Tokyo97 ellipsoid ($B_{Tokyo97}$, $L_{Tokyo97}$, 0) to WGS-84, obtaining new coordinates ($B_{WGS\text{-}84}$, $L_{WGS\text{-}84}$, dH). This dH corresponds to the height of the Tokyo97 ellipsoid above the WGS-84 ellipsoid near the triangulation point (Fig.6).
   b) Refer to JGEOID96 at ($B_{WGS\text{-}84}$, $L_{WGS\text{-}84}$), obtaining the geoidal height of $Hg_{WGS\text{-}84}$ above the WGS-84 ellipsoid.
   c) Subtract dH from $Hg_{WGS\text{-}84}$ to obtain the geoidal height $Hg_{Tokyo97}$ above the Tokyo97 ellipsoid.

2) Add $Hg_{Tokyo97}$ and Ho, obtaining the approximate ellipsoidal height $He'_{Tokyo97}$ of the considered point.

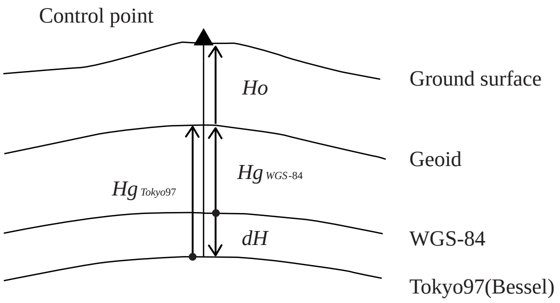


Fig. 6 Schematic geometry of a simple geoidal height conversion between nearly-aligned ellipsoids.

3) Transform Tokyo97 coordinates ($B_{Tokyo97}$, $L_{Tokyo97}$, $He'_{Tokyo97}$) to JGD2000 ($B'_{JGD2000}$, $L'_{JGD2000}$, $He'_{JGD2000}$) using the three transformation parameters at the Origin. Since these are dependent on JGEOID96, and not the final Geodetic Coordinates 2000, they are marked with'.

4) Refer to GSIGEO2000 at ($B'_{JGD2000}$, $L'_{JGD2000}$), obtaining the geoidal height $H_{JGD2000}$ of the considered point above the GRS80 ellipsoid of JGD2000.

5) Add $Hg_{JGD2000}$ to Ho to obtain the ellipsoidal height $He_{JGD2000}$ of the considered point above the JGD2000

ellipsoid.

6) Transform JGD2000 coordinates ($B'_{JGD2000}$, $L'_{JGD2000}$, $He_{JGD2000}$) to Tokyo97, obtaining ($B'_{Tokyo97}$, $L'_{Tokyo97}$, $He_{Tokyo97}$). $He_{Tokyo97}$ is the accurate ellipsoidal height of the considered point based on GSIGEO2000.
7) Transform Tokyo97 coordinates ($B_{Tokyo97}$, $L_{Tokyo97}$, $He_{Tokyo97}$) to JGD2000, obtaining the final Geodetic Coordinates 2000 ($B_{JGD2000}$, $L_{JGD2000}$) for non-GPS triangulation points.

The published Geodetic Coordinates 2000 contain the following positional information:

- newly-adjusted longitudes and latitudes based on the GRS80 ellipsoid in ITRF94 at 1997.0 epoch (= JGD2000),
- original heights of the Tokyo Datum, and
- geoidal heights above the GRS80 ellipsoid. Although these are derived from GSIGEO2000 for non-GPS triangulation points, they may deviate from GSIGEO2000 for GPS occupied triangulation points, where geoidal heights are determined by subtracting the heights above the sea-level from the adjusted ellipsoidal heights.

The last point implies an inconsistency problem of the height system in Geodetic Coordinates 2000, which should be handled in the near future.

4. Horizontal Geodetic Coordinates of 4th-order Triangulation Points by Transformation

This chapter describes the determination of Geodetic Coordinates 2000 of the 4th-order triangulation points, which have been established for controlling cadastral surveys since the 1950s. Because re-adjustment of these 64,000 points was not realistic, we decided to take the second best method by introducing a precise datum transformation program named TKY2JGD that uses local transformation parameter tables determined from the coordinate differences of the 1st- to 3rd-order triangulation points between JGD2000 and Tokyo Datum.

4.1 Local Transformation Parameters from Tokyo Datum to JGD2000

Employment of the Tokyo97 Datum enabled a two-step transformation from the Tokyo Datum to ITRF94. The first step is a transformation from the Tokyo to Tokyo97 Datum. As shown in Fig.5, differences in latitude and longitude (dB, dL) at the 1st- to 3rd-order triangulation points are complicated and difficult to model with one set of transformation parameters. Therefore, local transformation parameters are defined at each 1-km grid (i.e. 30-second in latitude, 45-second in longitude) by interpolating dB and dL at those triangulation points. The second step from Tokyo97 to ITRF94 is straightforward as described in Section 3.3.2. TKY2JGD combines these two transformations.

The Kriging method was used to interpolate local transformation parameters for each grid. Though the Kriging method is computationally intensive, recent high-powered CPUs allow computation of 380,000 sets of parameters at each 1-km grid. The new algorithms and the small grid interval provided transformation precision of 1.4 cm (Tobita, 2002). The parameters also cover 58 island areas.

4.2 Transformation using TKY2JGD

TKY2JGD is a convenient program that converts geodetic latitudes B and longitude L from the Tokyo Datum to JGD2000 within the precision of original 4th-order triangulation points in the Tokyo Datum. TKY2JGD reads the local transformation parameter table and conducts bilinear interpolation using parameters at four corners of a grid that includes the point concerned. Schematically, the Geodetic Coordinates of the 4th-order triangulation points are obtained by

$$\begin{pmatrix} B \\ L \end{pmatrix}_{JGD2000} = \mathrm{TKY\ 2JGD}\begin{pmatrix} B \\ L \end{pmatrix}_{Tokyo} .$$

Note that height information is not explicitly required here. In general, transformation parameters depend on the ellipsoidal height of the position, because the surfaces of the two ellipsoids are slightly inclined. To reduce this error, an ellipsoidal height for each grid is required. Actually, TKY2JGD uses JGEOD96 and 50m-spacing Digital Elevation Model (DEM) to calculate the ellipsoidal height for each grid by adding the geoidal height and the height above the sea-level.

To indicate regions that may have large transformation errors, mainly due to crustal deformation, an error index (square root of summation of squared gradient of dB or dL) was developed and the distribution of the index was mapped in color (Tobita, 2002). The grid data set and bilinear interpolation program can be used to transform coordinates of public control points and cartographic products, including digital maps in Geographic Information System.

5. Conclusions

In April 2002, Japan introduced a new geodetic reference system named the Japanese Geodetic Datum 2000 (JGD2000). JGD2000 is a geocentric system compliant with the world standard, and is more precise than the preceding Tokyo Datum. This has brought a giant leap for the Japanese geospatial community, allowing GPS as a main tool for positioning without coordinate conversion.

It was in 1993 that an internal working group at the Geodetic Department of GSI started technical discussions on the modernization of the Japanese geodetic reference system. After 9 years of preparation and calculation, the new Geodetic Coordinates 2000 of horizontal control points, i.e. the realization of JGD2000, were released to the public when the revised Survey Act of Japan came into effect on April 1, 2002. Recent advancement of GPS surveying and the establishment of GEONET, together with the long term efforts on VLBI observations and its collocation with GPS, were essential to achieve the adoption of a geocentric reference system. Repeated survey data at triangulation points played a key role in the densification of JGD2000. Table 10 summarizes the survey data used for the network adjustment for Geodetic Coordinates 2000, indicating that Geodetic Coordinates 2000 are the fruits of a long term effort of geodetic surveys in Japan.

The recent change of the geodetic reference system of Japan from the Tokyo Datum to JGD2000 is an ongoing process to keep the system precise and up-to-date for the various demands of modern society. In rapidly changing Japan over tectonic plate converging zones, and with the approach of the information society, the future direction of the geodetic reference system requires special thought. We now have a vision towards the establishment of a Geo-Referencing Infrastructure for Dynamic Japan (GRID-Japan), which supports various user demands to locate objects with any required precision, anywhere, anytime in Japan (GSI, 2003b; Komaki et al., 2003). Efforts to establish a semi-dynamic datum with online control point database have begun. At the same time, revision of the heights of triangulation points is now under preparation.

Table 10 Survey data used in the network adjustment for the realization of JGD2000 (as Geodetic Coordinates 2000)

Control Points / Survey Data Used	VLBI stations	Permanent GPS stations (GEONET)	Primary control points*	1st to 3rd order triangulation points	4th order triangulation points
Space Geodetic Network	7	951	1		
Highly Precise Geodetic Network (HPGN) surveys			493		
Connection surveys with GEONET			72	261	68
Primary Precise Geodetic Network (PPGN) Suveys			2,446		
Secondary Precise Geodetic Network (SPGN) Surveys			14	3,069	
Earthquake Recovery (ER) Surveys				2,657	
3rd order Triangulation Network (TTN) Surveys				***51,970*	
Isolated Islands Connection Surveys				97	5
Total	7	951	3,026	***58,054*	73

* Part of 1st and 2nd order triangulation points that have been occupied by EDM at PPGN surveys
** Sum of network adjusted points at each block. Includes overlapping points with adjacent blocks.

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The Generic Mapping Tools (GMT) were used to

create Plate 4, Figure 4 and 5 of the paper.

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