Reconstruction of Geodetic Reference Frame after the 2011 off the Pacific Coast of Tohoku Earthquake

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Key words: GNSS/GPS, Reference systems, Crustal deformation

SUMMARY

GNSS Earth Observation Network System (GEONET), dense GNSS continuous observation network of Japan, detected huge crustal deformation over a wide area of eastern Japan, caused by the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011. The deformation was so huge that positions of control points, GEONET stations, triangulation control points and leveling benchmarks, were largely changed. As a result, “Survey Results” of the points, officially authorized reference positions for all survey in Japan, could not keep inter-consistency with nearby points. Therefore, the Geospatial Information Authority of Japan (GSI) decided to stop the Survey Results and publicly announced it on March 14, 2011.

After the earthquake, the Survey Results were strongly required to be revised as soon as possible since they were essential basic information for various urgent restoration programs. However, large postseismic deformation still continued in the large part of the area and this meant that if we immediately revised the Survey Results, the postseismic deformation would soon make them inconsistent with real positions and unavailable for the restoration works. Therefore, we estimated the future postseismic deformation by extrapolating GEONET solutions into the future, and decided the optimal timings of the revision based on the estimation. Eventually, Survey Results of GEONET stations were first published on May 31, 2011 and those of triangulation control points and leveling benchmarks were done on October 31, 2011 respectively. In this paper we report reconstruction of national geodetic reference frame of Japan after the huge earthquake, more specifically, policy and process of the revision of the Survey Results of Japan.

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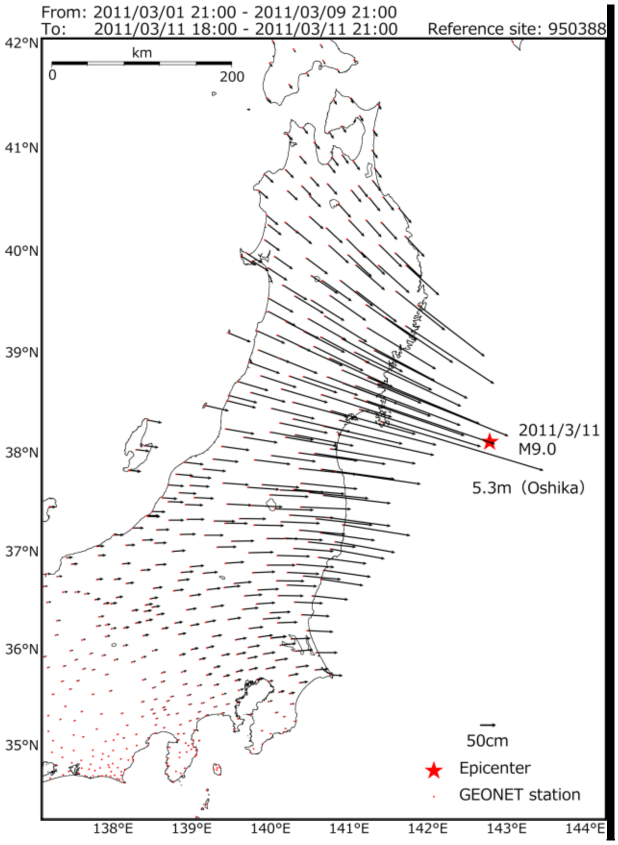
1. INTRODUCTION

The 2011 off the Pacific coast of Tohoku Earthquake (hereafter "Tohoku Earthquake") struck wide areas of eastern part of Japan on March 11, 2011. The earthquake was one of the largest seismic events human beings have ever experienced and the moment magnitude was 9.0. The event also triggered an extremely huge tsunami which exceeds people's expectation causing severe and catastrophic damages along the coast of the Tohoku and Kanto regions. Large-scale crustal deformation was also caused by the earthquake. The deformation was precisely detected by GNSS Earth Observation Network system (GEONET), GNSS continuous observation network of Japan, which has been operated by the Geospatial Information Authority of Japan (GSI) from 1996. The solution of GEONET shows that one of the GEONET stations, "Oshika", the nearest station to the epicenter, was moved about 5.3m to east-southeast and subsided about 1.2m at the time of the earthquake (Fig. 1). After the main shock, post-seismic deformation has continued widely along the Pacific coast of eastern part of Japan (ex. Ozawa et al., 2012). Several aftershocks also occurred and caused coseismic crustal deformation in relatively small areas (Fig. 2). Under those circumstances, it was obvious that national geodetic reference frame of Japan, "Geodetic Coordinates 2000" (Matumura et al., 2004), was already not consistent with real positions of the control points and the degree of the inconsistency was so large that the frame could no longer satisfy user's demands. This means that Survey Results of the control points, which are officially authorized coordinates/elevations for all surveys in Japan, became significantly different from their real positions and should no longer be accurate reference for the use for surveys.

2. AREA OF THE REVISING SURVEY RESULTS

Relative positions between nearby control points need to be as precise as required for land surveying. If the positions become inconsistent with nearby points, they can no longer be used for surveys and thus have to be revised as soon as possible. For example, after some previous large earthquakes such as Tokachi-Oki earthquake in 2003 and Iwate-Miyagi earthquake in 2008, which caused large crustal deformation, GSI stopped Survey Results at areas which were affected by the earthquakes in order to avoid regenerate inconsistent position information. At the cases, we developed source fault models of the earthquakes from coseismic deformation detected by GEONET, then estimated crustal strains of the earthquakes form the model and finally determined areas which needed the stop of Survey Results based on the crustal strains. We stopped Survey Results in an area where the model indicated strains exceeded 2ppm, which is equivalent to deformation of 2cm per 10km. According to this policy, we also stopped Survey Results of GEONET stations and triangulation control points in 16 prefectures on March 14, 2011, immediately after the earthquake (Fig. 3). On the same day, we also closed Survey Results of leveling benchmarks along the routes which have vertical deformation more than a few centimeters (Fig. 3).

GSI started calculation of the Survey Results of GEONET stations just after the Tohoku Earthquake. We first planned to revise Survey Results only in the area where strains of the earthquake exceeded 2ppm. However, during the evaluation of the Survey Results recalculated, it was revealed that not only coseismic deformation, but also accumulation of successive deformation caused by plate motions over long years have to be considered at the prefectures located adjacent to the southern margin of the area originally planned to be revised, which were Toyama, Ishikawa, Fukui and Gifu prefectures. At the boundary between the prefectures and the original area, the accumulation of deformation caused discrepancies over 10cm in the Survey Results. Therefore, we additionally stopped Survey Results of triangulation control points in these prefectures on May 31 (Fig. 3). The number of major control points as of March 11, 2011 and those with Survey Results stopped after the earthquake are listed in Table 1.



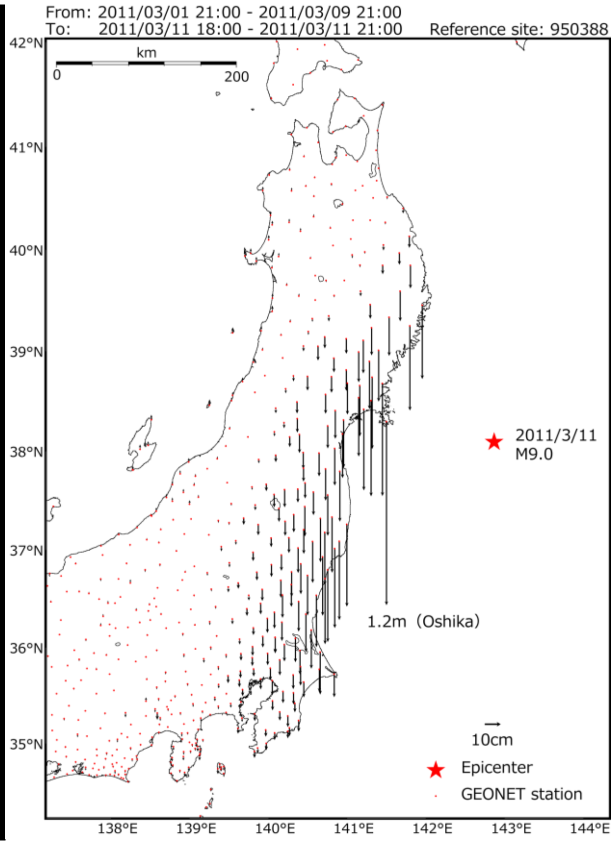


Fig. 1 Crustal movements caused by main shock of the 2011 off the Pacific coast of Tohoku Earthquake (Left: horizontal deformation, Right: Vertical deformation)

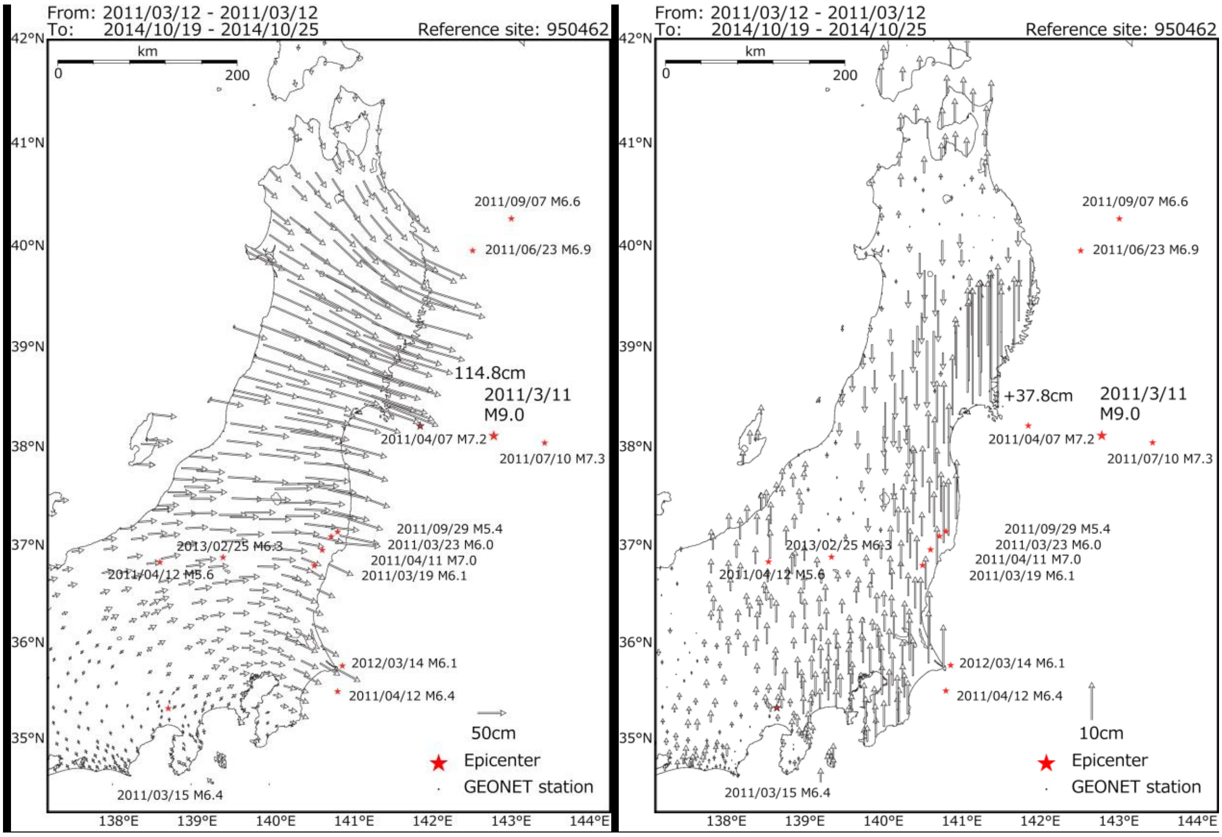


Fig. 2 Postseismic crustal movements caused by the 2011 off the Pacific coast of Tohoku Earthquake and coseismic crustal movements by its aftershocks (Left: horizontal deformation, Right: Vertical deformation)

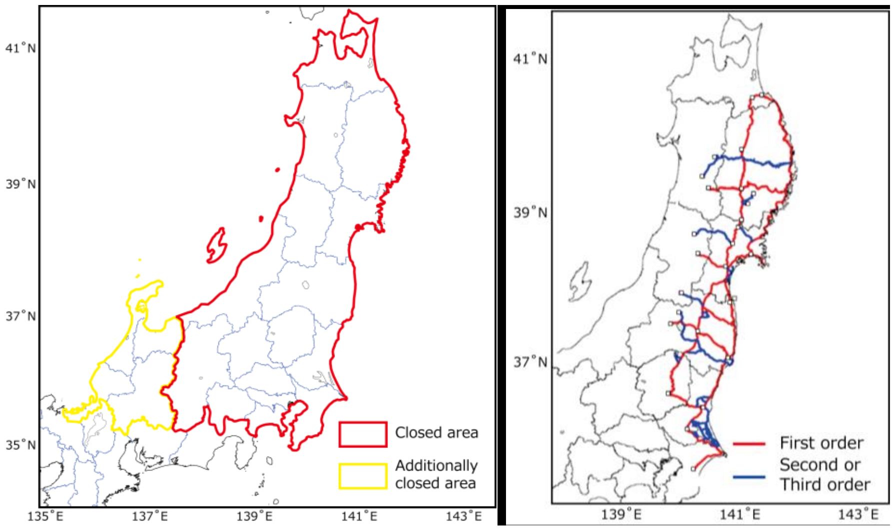


Fig. 3 Areas where horizontal Survey Results were closed (left) and leveling routes of which Survey Results were closed (right)

Table 1 List of the number of control points across Japan as of March 11, 2011 and the number of control points in 20 prefectures withheld from publication of Survey Results.

Type		Number of all points	No. of withheld points
GEONET station		1,240	438
Triangulation Control points (109,074)	First order triangulation control points Second order triangulation control points Third order triangulation control points Fourth order triangulation control points	975 5,060 32,326 70,713	353 2,140 15,170 26,194
Benchmarks (18,239)	First order bench marks Second order bench marks	14,768 3,471	991 388
Total		128,553	45,674

3. Required Accuracy and Date of Revision for Survey Results of GEONET Stations

Acceptable error range for GNSS surveying in Japan is defined in the General Standard of Operation Specifications for Public Surveys. In accordance with the standard, the accuracy required for Survey Results of GEONET Stations should be better than 2ppm in positions relative to nearby GEONET stations. Restoration/reconstruction works in disaster-stricken areas heavily depend on accurate position information. GEONET stations were the key enabler for prompt resuming of provision of such information. Therefore, prompt revision of Survey Results of GEONET stations was strongly desired. However, postseismic crustal deformation was continuing in the disaster affected areas and the rate was tens of centimeters a month in maximum (Fig. 4). Although the rate was gradually decreasing, it was expected to continue tens of years. This means if we immediately revised the Survey Results, the postseismic deformation would soon make them inconsistent with actual positions and unavailable for the restoration works.

In order to know the best timing for the revision, we estimated future deformation by extrapolating coordinate time series of GEONET with a logarithm function by Marone et al. (1991) as follows:

$$y(t) = c + a\ln\left(1 + \frac{t}{\tau_{\log}}\right) \quad (1)$$

where c and a are the constants, $\tau_{\log}$ is the time constant and t is the time from the earthquake. Figure 4 shows the estimated deformation at GEONET station "Yamada" (No.950167), which is located along the Pacific Coast of Miyagi Prefecture. The estimation indicated that the deformation rate would gradually decrease and make a slightly steep change around May 2011. Based on the estimation, we decided the new Survey Results of GEONET should be released by the end of May.

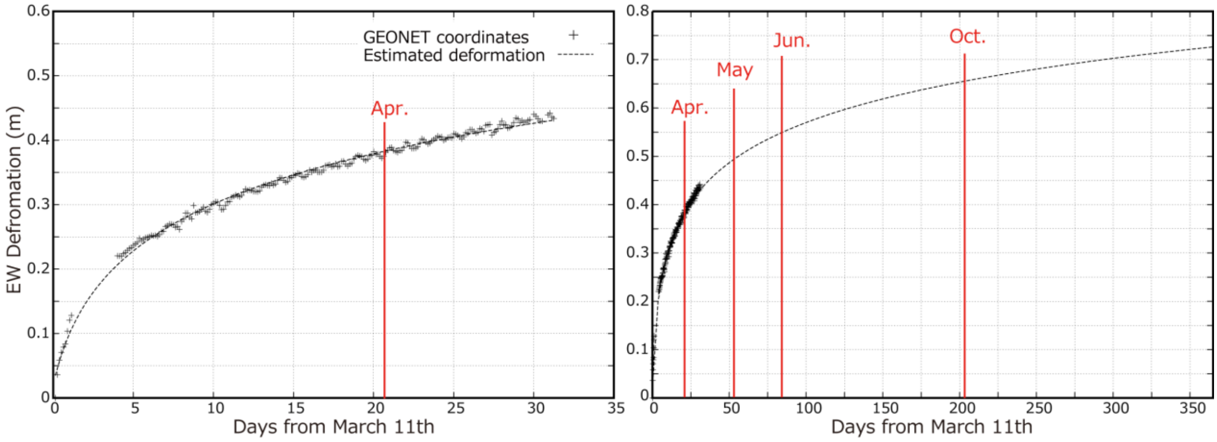


Fig. 3 Postseismic deformation observed at GEONET Station No. 950167 (cross) and estimated postseismic deformation (dotted line) in short term (left) and long term (right)

4. CALCULATION OF SURVEY RESULTS OF GEONET STATIONS

In order to keep consistency with nearby control points, Survey Results are usually calculated by fixing positions of surrounding control points as reference points. However, crustal deformation caused by the Tohoku Earthquake was so huge that the positions of all control points in the eastern part of Japan were largely changed and we could not revise the Survey Results with the ordinary procedure. Therefore, we had to determine new positions of all the points including the Origins of the Horizontal/Vertical Control Network of Japan instead of determining them from positions of nearby points. First, we calculated coordinates of VLBI (Very Long Baseline Interferometry) station at GSI headquarters in Tsukuba, TSUKUB32, in International Terrestrial Reference Frame 2008 (ITRF2008) and then calculated coordinates of almost all GEONET stations in the area indicated in Figure 3. The calculated coordinates was adopted as new Survey Results.

In Hokkaido and the western part of Japan, where the crustal deformation was relatively small, we decided not to revise the Survey Results because the deformation did not affect inter-consistency of positions of control points in the area while the revision would require all social activities additional time and cost for adopting the new position infrastructure. At the boundary between eastern and western Japan, we recognized inconsistency between the existing and updated Survey Results. The inconsistency was over 10cm in maximum. Therefore, we solved the gap by correcting them with a model described in 4.1.3 in order to ensure the accuracy required for survey.

4.1 Calculation of Survey Results for VLBI and GEONET stations

We hierarchically calculated the Survey Results of the control points in coordinates from VLBI station, GEONET stations to triangulation control points.

4.1.1 Coordinates of TSUKUB32

First, the coordinates of TSUKUB32 on ITRF2008 were estimated from a session of the International VLBI Service for Geodesy and Astronomy (IVS), "IVS-R1482", which was conducted on May 10, with ITRF2008 coordinates of five overseas VLBI stations constrained. Coordinates of the other control points in the area including GEONET stations were calculated based on the coordinates of TSUKUB32.

4.1.2 Calculation Procedure

The calculation procedure for Survey Results of VLBI and GEONET stations is as follows.

(1) We first calculated postseismic deformation of GEONET station No.92110 at GSI headquarters in Tsukuba from the difference between averages of 5days GEONET R3 solution at May 8-12 and at May 22-26. Next, we calculated the coordinates of TSUKUB32 at 12:00 UTC, May 24 by adding the postseismic deformation to the coordinates of TSUKUB32 at 5:00 UTC, May 10 which was calculated from VLBI observation.

(2) The coordinates of GEONET stations in ITRF2005 at 12:00 UTC, May 24 were calculated by averaging 3 days GEONET R3 solutions of May 23-25. Then, the ITRF2005 coordinates were translated to ITRF2008.

(3) We collocated the coordinates (1) and (2) with the local tie at 2007 (Miura et al., 2009) and fitted the ITRF2008 GEONET coordinates to the coordinates of TSUKUB32 so that the coordinates of GEONET stations were consistent with the coordinates of the IVS solution. The fitted ITRF2008 GEONET coordinates were adopted as Survey Results of GEONET Stations. Orthometric heights of the GEONET stations were calculated by subtracting geoid heights of the latest Geoid Model of Japan at the time, GEIGEO2000 (Kuroishi et al., 2002), from ellipsoidal heights of each GEONET Station. The orthometric heights were calculated and revised again on April 1, 2014 at the time of the release of the latest Geoid Model of Japan , GSIGEO2011 (Miyahara et al., 2014).

4.1.3 Adjustment on Boundary Area

Before the Tohoku Earthquake, geodetic reference frame of Japan was “Geodetic Coordinates 2000”, which was published in January 1, 1997. In western part of Japan, crustal deformation by the earthquake was not so large and thus crustal strains between nearby control points was under 2ppm. As a result, the deformation did not cause inconsistency in Survey Results. Therefore, we decided not to revise the Survey Results in western part of Japan. However, crustal deformation had been accumulated throughout Japan because of successive plate motions, and this caused discrepancies in Survey Results at the southern boundary of the revised area. The discrepancy was up to 10cm in horizontal components. Thus, we decided to revise Survey Results of GEONET stations in additional four prefectures indicated in Figure 3. The corrections for the additional area were calculated in order to distribute the large gap at the boundary into the whole area so that the discrepancy was decreased to acceptable order throughout the area. On the other hand, for the northern boundary, a strait lies between Hokkaido and the mainland of Japan and thus surveys across the strait are not common. Therefore, the corrections were applied only to area outside of the southern boundary. The corrections were also not applied for elevations, because we confirmed discrepancies in the elevations did not exceed the acceptable error range specified in the General Standard of Operation Specifications for Public Surveys.

The differences between the new and previous Survey Results at each GEONET station are shown in Figure 4. The diffrences are as large as 5m along the Pacific coast of Tohoku region whereas progressively decreasing as getting closer to the southern boundary . It was also confirmed that discrepancies in the additional four prefectures were mostly smaller than 2ppm, which would not have negative effects on surveys across the boundary.

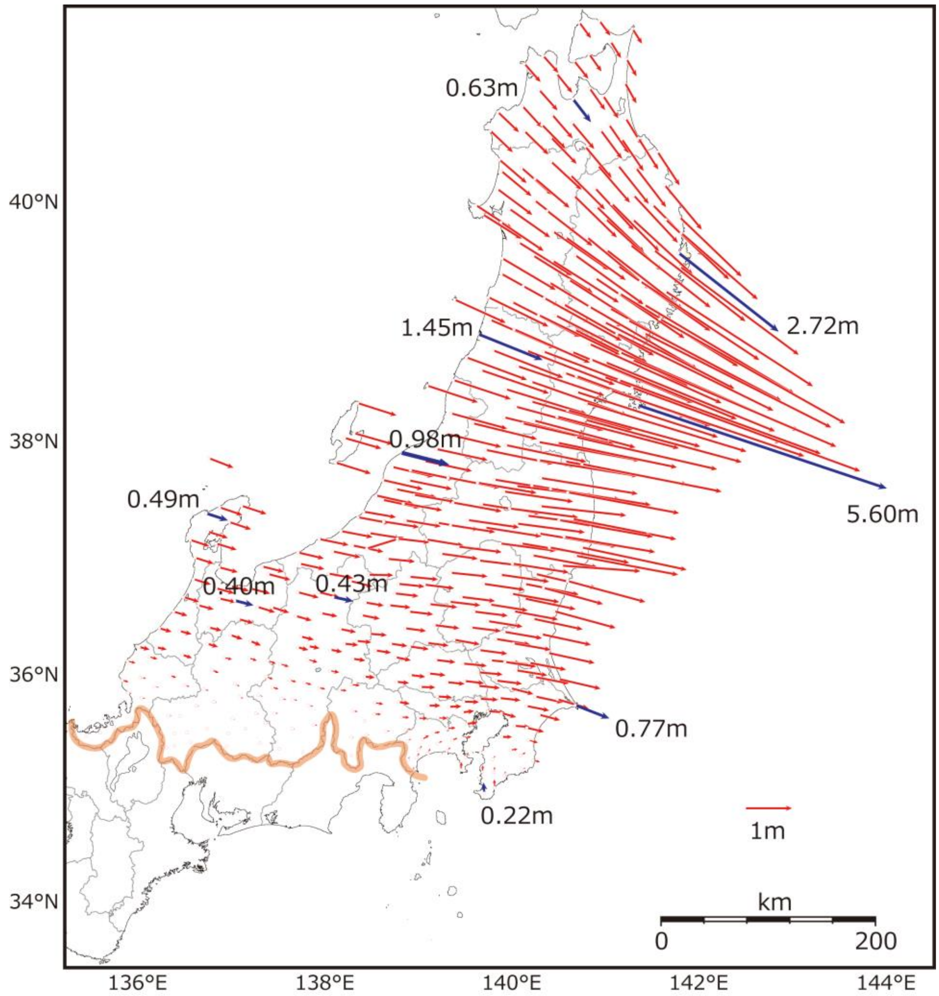


Fig. 4 Differences in horizontal components between Survey Results of GEONET stations before and after the revision

4.2 Re-publication of Survey Results of GEONET Stations

The new Survey Results of 438 GEONET stations were released on May 31, and in the area indicated in Figure 3, GEONET stations became available as reference points for all surveys including public surveys. On the same day, Survey Results of triangulation control points of four prefectures, Toyama, Ishikawa, Fukui and Gifu, were stopped as already mentioned in Chapter 1.

5. AMENDMENT OF THE HORIZONTAL/VERTICAL ORIGINS OF CONTROL NETWORK OF JAPAN

In Article 11 of the Survey Act, it is stated that in basic or public surveys, positions must be represented by geographical latitude and longitude and height above mean sea level. The Article 11 also states that the origin for the geographical latitude and longitude is Origin of the Horizontal Control Network of Japan, "Nihon Keiido Genten" in Japanese, and the origin for the mean sea level is Origin of the Vertical Control Network of Japan, "Nihon Suijun Genten" in Japanese. The positions and coordinates/elevation of the origins are respectively prescribed in Article 2, Paragraphs 1 and 2 of the Order for Enforcement of the Survey Act.

The positions of the Origins of the Control Network of Japan were also changed by the Tohoku Earthquake. The horizontal origin moved to east approximately 27cm and the vertical origin subsided approximately 2.4cm. As a result, the prescribed coordinates and elevation became inconsistent with real positions, and the coordinates and elevation on the Order had to be amended to ensure the accuracy of surveys.

5.1 Amendment of Coordinate of the Origin of the Horizontal Control Network of Japan

GNSS observations were conducted between June 21 and 25 at the VLBI marker of TSUKUB32, which is installed on the GSI headquaters in Tsukuba, as well as at the Origin of the Horizontal Control Network of Japan in Tokyo in order to determine new coordinates of the Origin. The coordinates of the Origin were newly calculated by adding the baseline vector of the observation to the coordinates of TSUKUB32 described in 4.1.2. The azimuth from the Origin to the VLBI marker of TSUKUB32 was also newly calculated. Table 2 shows the new coordinates and azimuth. The new position moved approximately 27cm to east relative to the previous potision.

Table 2 Amended coordinates of the Origin of horizontal Control Network of Japan and azimuth from the Origin to the VLBI marker at GSI headquarters in Tsukuba

Longitude Latitude	139°44′28″.8869 35°39′29″.1572
X (m)	-3959340.203
Y (m)	3352854.274
Z (m)	3697471.413
Azimuth	32°20′46″.209

5.2 Amendment of Elevation of the Origin of the Vertical Control Network of Japan

Reference surface for the vertical control network of Japan is the mean sea level of Tokyo Bay. Long time at the Aburatsubo tidal gauge station from 1920's, which represents the mean sea level in Tokyo Bay, showed that there was no significant change in tides associated with the Tohoku Earthquake. Although GPS stations, "P Aburatsubo" at the Aburatsubo station and nearby GEONET station "Miura 2", subsided by several centimeters at the earthquake, there was no significant change in ellipsoidal height at the Aburatsubo station because the coseismic subsidence was cancelled out with following postseismic uplift. The pre-earthquake GEONET solutions of January 2011 and the post-earthquake of July 2011 shows almost the same height at the both GNSS stations. Therefore, elevation of the Origin of the Vertical Control Network of Japan was newly calculated through the following procedures (1) and (2) and then verified by (3).

(1) Height of the reference benchmark at the Aburatsubo station was determined to be 2.4173m based on spirit leveling prior to the earthquake between the Aburatsubo station and the Origin in January 2011 because we assumed the earthquake did not change height of the reference benchmark relative to the mean sea level.
(2) On the other hand, relative height between the Aburatsubo station and the Origin was assumed to be changed by the earthquake. Therefore, the new elevation of the Origin was calculated from the elevation of the reference benchmark at the Abratsubo station obtained in (1) based on spirit leveling in July 2011 and then determined to be 24.3904m.
(3) The elevation of the Origin was individually calculated based on spirit leveling between the VLBI marker for TSKUB32 and the Origin in order to verify the value obtained in (2). The evelation determined in (3) was 24.4007m.

The standard deviation of network adjustment of the leveling indicates values shown in (1) and (2) have a possibility to contain error of +/-0.0026m. Taking the error into account, the newly amended elevation of the Origin should be 24.3900m after rounding (3) off to four decimal places.

5.3 Amendment of the Order for Enforcement of the Survey Act

Since the coordinates/elevation of the origins of the Horizontal/Vertical Control Network of Japan were prescribed respectively in Article 2 of the Survey Act, Paragraphs 1 and 2 of the Order for Enforcement of the Survey Act, the order needed to be amended. The amendment should be primarily conducted before the revision of any other control points because the Article 11 stated Survey Results of control points have to be expressed relative to the origins. After being processed through required procedures, a cabinet decision on the amendment of the Order for Enforcement of the Survey Act was reached on October 18, 2011, followed by promulgation and implementation on October 21, 2011.

6. Revision Of Survey Results Of Triangulation Control Points

To ensure accuracy of Survey Results of all triangulation control points in the revised area, it was preferable that we resurveyed all the points and calculated the new positions based on the surveys on-site. However, the number of the points in the area of which Survey Results were stopped exceeded 40,000. Resurveying all the point would be so time- and cost-consuming that it was practically almost impossible to conduct resurveys at all the points. Deformation caused by an earthquake basically follows physical mechanism of the earthquake source fault and thus the deformation caused by the earthquake can approximately be estimated from the earthquake fault model. Especially in large earthquakes, the model well produces the real deformation and the deformation is very similar within small area. Therefore, at the past large earthquakes such as Tokachi-ok Earthquake in 2003 (Doi et al., 2005), instead of resurveying all the points in the affected area, we selected some points from the area and resurveyed them assuming the points represented the trend of the deformation of the area. Then, we calculated correction parameters for Survey Results by interpolating the deformation at the selected points. For the other points which were not resurveyed, the Survey Results were determined by adding the correction parameters to previous Survey Results. We adopted the same procedure for the Tohoku Earthquake as the past large earthquakes, and revised latitudes and longitudes of triangulation control points in 20 prefectures including Tokyo. In addition to the horizontal components, significant coseismic deformation over 10cm was detected in elevations at six prefectures of the Tohoku region and also at Ibaraki prefecture. Certain amount of postseismic deformation was also continued in elevations along the Pacific coast from Aomori to Ibaraki. Therefore, elevations of triangulation control points also needed to be revised with the correction parameters in these areas. One of the largest aftershock of the Tohoku Earthquake occurred near the boundary between Nagano and Niigata prefectures on March 12, 2011, and elevations of this area were also revised.

6.1 Resurvey of Triangulatin control points

Within the area where Survey Results was stopped, we selected 595 points and resurveyed them by precise GNSS observation of at least 6 hours. Also, we conducted resurvey of 1,272 triangulation control points along the Pacific coast which was close to the epicenter and tsunami devastated sites, near the Nagano-Niigata boundary and at the middle of Fukushima prefecture where one of the largest aftershocks occurred on April 11. In those areas, triangulation control points were severely damaged by the earthquakes and tsunami.

For the four prefectures near the southern boundary, Toyama, Ishikawa, Fukui and Gifu, the spatial density of the precise GNSS observation was not enough. In the area, the deformation was relatively small and some of the triangulation control points had GNSS data observed before the Tohoku Earthquake. Therefore, we recalculated Survey Results with the data by fixing the revised Survey Results of nearby GEONET stations.

In areas where aftershocks of the Tohoku Earthquake caused large local crustal strains, we conducted resurveying at 158 triangulation control points and released the Survey Results in May and June, 2012. An area near the new clear power plant in Fukushima was off-limits after the Tohoku Earthquake, and some part of the area was reopened in 2012. For the reopened area, we also couducted resurvey of 29 triangulation control points and released the Survey Results in December 2012.

6.2 Correction Parameters

The correction parameters for both horizontal coordinates and elevations of triangulation control points were developed by interpolating differences between the previous and revised Survey Results of 587 GEONET stations and 667 triangulation control points. The parameters were constructed by estimating differences between previous and new Survey Results at the southwest corner of third-order mesh, which spacing is approximately 1km, using Kriging method.

The parameters can be used not only for recalculation of triangulation control points but also available to all users for translating positions of public or other control points from old to new geodetic coordinates. Therefore, we evaluated the accuracy of the parameters in advance of the release of the parameters. The comparison between differences of the Survey Results and the correction parameters at 1,092 GEONET stations and triangulation control points shows the reproduction errors of the parameters in the standard deviation were 3mm in north-south component and 4mm in east-west component. The maximum difference is 1.9cm in positive and 2.4cm in negative in the east-west component. Next, we conducted an external evaluation of the parameters at 1,295 triangulation control points by comparing coordinates calculated through the correction with those determined through field surveys. The result showed that more than 90% of the points are consistent with the parameters within 10cm for horizontal coordinates and within 20cm for vertical elevations. Several points showed large discrepancies over 50cm. However, such are extremely rare, and it was highly likely that the previous Survey Results themselves contains errors.

It should be noted that areas without correction parameters in Fukushima indicated in Figure 5 is still off-limit and resurvey cannot be conducted. Survey Results are also still closed in the areas.

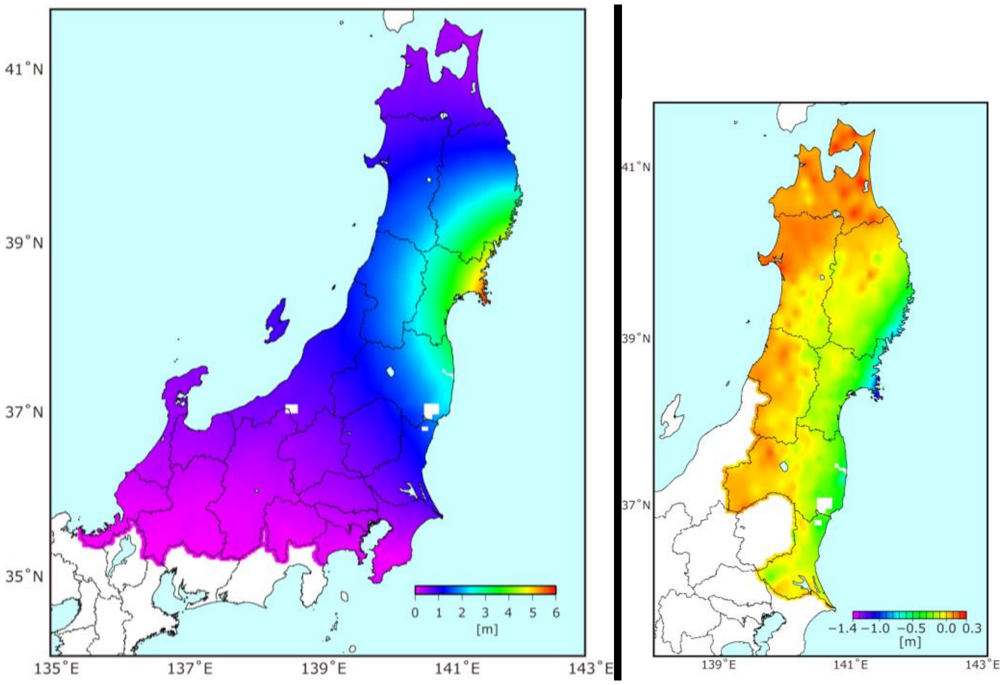


Fig. 5 Correction parameters for horizontal coordinates (left) and elevations (right)

6.3 Recalculation of Survey Results of Triangulation Control Points

We calculated Survey Results of remaining 41,392 triangulation control points using PatchJGD, the software for correcting geodetic coordinates of Japan (Tobita, 2009), which was developed by GSI. For the reopened area near the new clear power plant in Fukushima, we also calculated Survey Results of additional 418 triangulation control points in December, 2012.

7. REVISION OF SURVEY RESULTS OF LEVELING BENCHMARKS

The accuracy of the correction parameters for elevations of triangulation control points was estimated around 10 to 20cm and thus did not satisfy the accuracy required for correction parameters of benchmarks which was required accuracy from 0.1 to 1mm. Therefore, Survey Results of benchmarks essentially needed to be revised through resurveys of benchmarks, instead of correction with estimated parameters. We conducted high-precision leveling along leveling routes of 3,660km mainly in the Pacific Coast area of the Tohoku and Kanto regions after the earthquake. Then, elevations of the benchmarks were calculated by network adjustment with multiple reference points based on the updated elevation of the Origin of the Vertical Control Network of Japan.

In terms of consistency with the Origin, the network adjustment should be done using the origin as an only reference point. However, the network of revised leveling routes was widely spread across the whole area of eastern Japan and the origin located near the southern margin. Therefore, benchmarks located near the northern boundary were distant from the Origin and if we conducted network adjustment using the origin as a single reference point, the benchmarks near the northern boundary would have discrepancies with those of outside the area. Therefore, we selected one more reference point for the network adjustment, a first-order benchmark 5527-2 in Iwate prefecture, in addition to the origin. The adjustment was conducted with two reference points, the Origin of the Vertical Control Network of Japan which was located near the southern boundary, and the first-order benchmark 5527-2 which was located near the northern boundary (Fig. 6).

Revised Survey Results of 1,897 benchmarks obtained by the network adjustment were released on October 31. Figure 6 shows the difference between the revised Survey Results and the previous Survey Results, Geodetic Coordinates 2000.

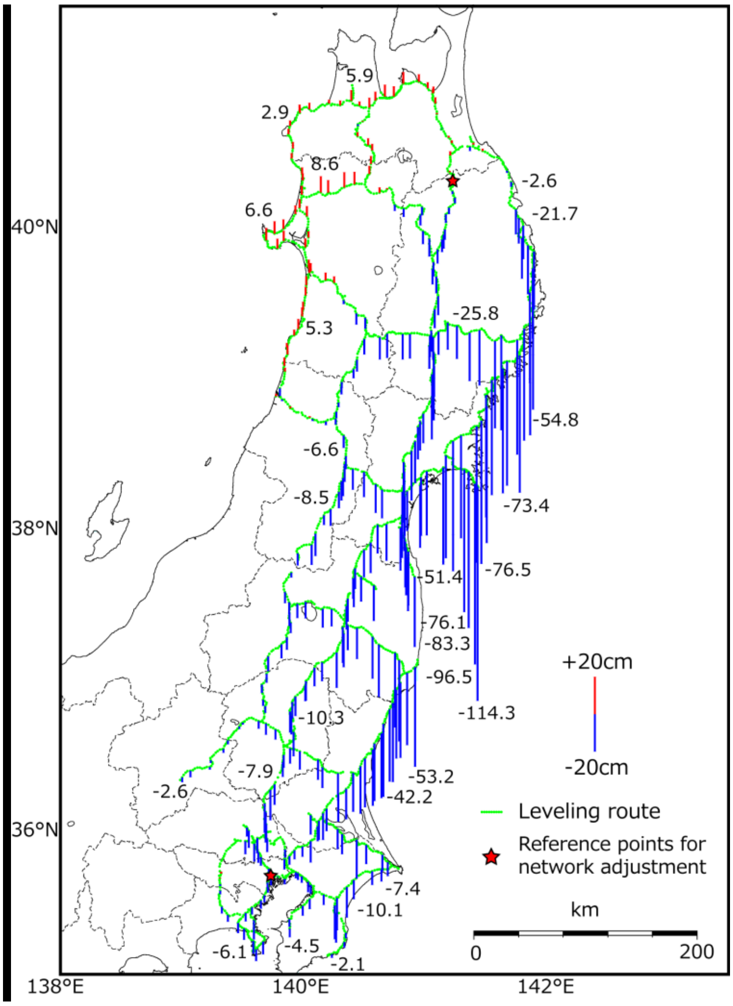


Fig. 6 Difference in elevations between Survey Results of leveling benchmarks before and after the revision.

8. GEODETIC COORDINATES 2011

Survey Results of GEONET stations were revised on May 31. The coordinates/elevation of the Origins of the Horizontal/Vertical Control Network of Japan were also updated on October 21. Finally, the revised Survey Results of triangulation control points and benchmarks were released on October 31. In order to raise awareness of users, the new geodetic reference frame of Japan which was consisted of the revised Survey Results was newly named "Geodetic Coordinates 2011".

9. CONCLUSION

Huge earthquake occurred off the Pacific coast of Tohoku, Japan caused extremely large crustal deformation over a wide area of eastern Japan, which necessarily caused stop of Survey Results of control points in 16 prefectures and of benchmarks from the Tohoku to Kanto regions on March 14, 2011, following additional stop in several areas on May 31 2011.

In order to provide accurate positions for restoration/reconstruction work in the disaster-stricken area, GSI immediately calculated the Survey Results of 438 GEONET stations and release the new Results on May 31. The timing of the release was decided by considering an influence of the future postseismic deformation estimated form GEONET solutions.

Survey Results of 595 triangulation control points were calculated from precise GNSS observations and those of additional 74 points were recalculated from past GNSS observation. Resurveys of 1,272 triangulation control points were also conducted in areas where the earthquake, its aftershocks and the tsunami destroyed control points. Correction parameters for the remaining points were developed by interpolating the differences between the previous and new Survey Results of 587 GEONET stations and 668 triangulation control points. Survey Results for the other 41,392points were revised through calculations using the correction parameters.

The revision of Survey Results of benchmarks was essentially conducted through resurvey considering the accuracy required by following surveys. High-precision leveling were conducted in the Tohoku and Kanto regions and network adjustment was conducted using the two benchmarks, the Origin of the Vertical Control Network and the first-order benchmark 5527-2, as reference points.

Survey Results of GEONET stations were revised on May 31. The coordinates/elevation of the Origins of the Horizontal/Vertical Control Network of Japan were also updated on October 21. Finally, the revised Survey Results of triangulation control points and benchmarks were released on October 31. The correction parameters were also provided to users on the same day. In order to raise awareness of users, the new geodetic reference frame consisted of the revised Survey Results was newly named "Geodetic Coordinates 2011".

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