Construction of GSI's Nationwide GPS Array

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ABSTRACT

The Geographical Survey Institute has operated the nationwide GPS array since October 1994. This network is designed both for crustal deformation monitoring and to serve as a highly precise geodetic network in the GPS age. This network has precisely monitored crustal deformation within several millimeters horizontally and several centimeters vertically. Most of the processing is carried out automatically.

This network is the densest GPS array in the world. It consists of 949 observation sites, and data analysis center in GSI campus for daily processing. In this system, three major software, Bernese, GAMIT, and GIPSY are all available. Since we collected more than one-year data, we estimated horizontal crustal velocity field with respect to stable interior of the Eurasian plate by using one-year continuous data. The result suggests that a plate boundary runs from Shizuoka to Niigata. The western half of it moves eastward except for the southern part of Shikoku Island and Kii Peninsula, where interplate coupling between the Eurasian plate and the Philippine Sea plate is observed. On the other hand, the eastern half moves westward.

1. INTRODUCTION

Japan is located on an extremely active tectonic region. As is known, four plates, the Eurasian (or the Amurian) ,the North American (or the Okhotsk) ,the Philippine Sea, and the Pacific plates, are interacting, and crustal strain is continuously accumulating, so it is inevitable that large earthquakes occur in Japan as the strain releases. Such strain accumulation is observed as a crustal deformation in some cases. Therefore, it is important to monitor the crustal deformation using geodetic data in order to understand the tectonic situation of the crust.

Historically, triangulation and triangulation data have been used to study regional tectonics; while VLBI (Very Long Baseline Interferometry) and SLR (Satellite Laser Ranging) are used to investigate global tectonics such as plate motion. In addition to these techniques, GPS (Global Positioning System) and SAR (Synthetic Aparture Rader) are becoming great tools for tectonic study. GPS has several advantages for tectonic study compared to other techniques. For example, data are collected continuously on every site. Also, GPS is cheaper and more compact, and therefore it is easier to construct lots of observation stations than it is with other space geodetic systems. Regarding spatial resolution, GPS is not superior to SAR, so, recently, attempts to integrate GPS and SAR data have been made.

In April 1994, the Crustal Dynamics Department began to operate the COSMOS-G2 (Continuous Strain Monitoring System with GPS by GSI) (Iwata 1994; Sagiya et al, 1995) in order to monitor the crustal deformation in South－Kanto and Tokai areas. After that, in October, 1994, the Geodetic

Department also began to operate the nationwide GPS array, Grapes (GPS Regional Array for Precise Surveying/ Physical Earth Science) (Iimura et al, 1994, Miyazaki et al, 1996) . Both networks successfully detected coseismic and potseismic displacements associated with earthquakes. But, the mean distance of Grapes sites was about 100km, which was not enough to monitor local crustal deformation. Also, to construct active controlling points by GPS, the number of Grapes sites was far from enough. To achieve these purposes, GSI combined COSMOS-G2 and Grapes, and added 739 new sites; the number of sites is now 949 in total. This network is named GEONET (GPS Earth Observation Network).

2. THE OUTLINE OF THE NEW GSI's GPS ARRAY

GEONET consists of 949 permanent GPS observation stations in Japan and a data analysis center at GSI in Tsukuba. The outline of the system is presented in this chapter.

2.1 Observation station

Figure 1 shows a picture of an antenna station pillar at Umaji (Kochi pref) station. Requirements for the observation station are:

(1) stable ground,

(2) wide over-view to avoid cutting off of signal,

(3) electric power supply,

(4) availability of telephone lines, and

(5) accessibility to the point for maintenance.

As a result, most of sites are in school campuses or parks in the suburb.

Each GPS station consists of a tower, an antenna, a GPS receiver, data transfer instruments, and an electric battery for emergencies. The tower is made of stainless steel and is 5m high with a 2m firm ground base. The tower can endure strong winds up to 60m/s. For temperature control in the storage box, a ventilator and a heater are attached. The antenna is mounted on the top, and the GPS receiver and data transfer instruments are placed in the central body of the tower (Figure 2) . The data obtained is transferred to the data analysis center at GSI in Tsukuba through public telephone lines. Since this system uses 24-hour data every day, the digital telephone line ISDN (Integrated Services Digital Network) is used for most of sites to reduce communication costs. Several stations still use analog telephone lines because ISDN is not available. They will be replaced with ISDN as soon as it becomes operational in those areas.

At most sites, sampling rate is 30 seconds, but at 120 sites, the data sampling rate is one second, among which 30 seconds data are usually transferred to Tsukuba. When trigger is pulled by a shake, one second sampling data are stored by the receiver and transferred. We use Trimble 4000 SSi and SSE for 704 sites, TOPCON GP-RIDY (equivalent of Ashtech Z-12) receivers for 211 sites, and , Leica receivers for 34 sites, all of which can receive carrier phase data and P-code data even under the A-S (Anti-Spoofing) condition.

Every receiver has enough internal memory to retain about 10 days of data in case of an emergency situation. Option of data transfer and observation programs can be changed from data analysis center through telephone lines. During an electrical power outage, the electric battery can supply electricity for five hours.

2. 2 Data analysis center

The data analysis center is located at GSI in Tsukuba. It consists of data management servers, analyzing servers, a data supplying controlling server, a data transferring server, and so on (Figure 3).

Data management servers download observation data from each site at a certain time every day. The data from each station amounts to 1 MB per day except for 1-second sampling data, which amounts to 30 MB. It takes about 3～20 minutes to transfer the data. Since 32 telephone lines are available, it takes about 3.5 hours to complete data transfer for the entire network every day. Analyzing servers process baseline analysis and display site displacement, strain, and temporal variation of baseline vector component. The data controlling server presents data into an disk array system which can store 420 GB data. Data and solution files are classified into several categories: raw data, RINEX data, solutions of baseline analysis, and solutions of network adjustment. Data stored in disk array are always available online.

3. DATA PROCESSING

3. 1 Overview

Although the precision of one session of GPS observation is, in general, worse than that of VLBI (Very Long Baseline Interferometry) and SLR (Satellite Laser Ranging), the accuracy is better than them as long as the observation is continuously taking place everyday.

Recently, the repeatability of continuous GPS observation is, typically, 5 mm horizontally and 1. 5 cm vertically.

In addition to that, we can improve the accuracy by using appropriate statistical analysis methods, such as trend estimation or detection of outliers. Thus, it is becoming increasingly feasible to understand both global and regional crustal deformation.

In order to achieve this goal, we have adopted of three major GPS analysis software's for routine processing; one is BERNESE developed by Bern University in Switzerland, the second is GAMIT/GLOBK developed by MIT (Massachusetts Institute of Technology) and SIO (Scripps Institution of Oceanography, University of California at San Diego) in the U. S., and the third is GIPSY developed by JPL (Jet Propulsion Laboratory) in the U. S.

Since these software's estimate the tropospheric delay of radio waves simultaneously, precision is also getting better in these days: typically 5 mm horizontally and 1.5 cm vertically.

Directory Structure

The directory /DM/NewGard is where the software's and configuration files are stored. There are subdirectories for each software package that store information about the solution types and strategies that have been defined for each software system. There are two subdirectories that store information about what solution types (stif) and strategies (strat) are available to the system. Additional configuration files are stored in /DM/NewGard and /DM/NewGard/ ⟨pkg.⟩ (⟨pkg.⟩ is the name of the selected software package). The basic structure is displayed in Figure 4.

The stif file is essentially input /

output files (iof) without full session information. GEONET uses the stif file as a template to generate the iof files that are given to the various software packages when an actual session is started. It will be the job of GEONET job submission routine to determine the session information.

The strat file defines what strategies are available. The contents of these files are only the description of what the strategy is and is used by GEONET in order to know what strategies are available. The actual strategy has to be developed and implemented within the native software system.

3. 2 Analyses Strategies

In daily processing, we are currently using both combined ephemerides (rapid/predicted ephemerides) and IGS final ephemerides. The precision of combined ephemerides is worse than IGS final ephemerides. Therefore, in this paper, we will show only the analysis strategy with IGS precise final ephemerides.

3. 2. 1 BERNESE

The basic idea for BERNESE processing is displayed in Figure 5. First, we divide the entire network into two clusters by receiver/antenna types. Both clusters include Tsukuba site, so, at the first stage, ITRF coordinates of these two Tsukuba sites are obtained from Tsukuba-IGS site. Next, two clusters are processed by giving tight constructs to these two sites. Trimble cluster consists of 704 sites. It is still difficult to process as one cluster, so we divided this cluster into a backbone cluster and regional clusters. The back-bone cluster, displayed as Figure 6, is a nationwide, sparse cluster, and ITRF coordinates of each site are obtained through Tsukuba-Trimble site. Also, each regional cluster, displayed in Figure 7, is processed, and then, combined with backbone cluster through several sites commonly involved both in backbone and regional clusters.

Ashtech cluster and Leica cluster are processed as one cluster, respectively (Figure 8, Figure 9) , and ITRF coordinates are obtained through Tsukuba-Ashtech, Tsukuba-Leica site, respectively.

Thus, all site coordinates are obtained in ITRF coordinate.

3. 2. 2 GAMIT / GLOBK

GAMIT / GLOBK processing takes place in two steps. In the first step, GAMIT analyzes data from user-specified and automatically determined clusters of stations to create loosely constrained (but ambiguity-resolved) estimates of station coordinates. In the second step, GLOBK combines these GAMIT output files to create solution files in the SINEX format, containing loosely constrained estimates for the entire network. The scheme could be adopted for clusters as small as two stations or as large as the memory and swap allow dimensioning of GAMIT. However, initial testing has been restricted to 20- and 35- Station clusters — large enough to make cleaning and ambiguity resolution robust but small enough to keep GAMIT run times reasonable. Also, the procedure for selecting stations for clusters is currently as follows: stations are first sorted by antenna type and then within each antenna grouping are selected in latitude bands to fill each cluster as evenly as possible up to its maximum number, with two stations overlaps. This software is now under examination, so a detailed strategy has not been decided yet.

3. 2. 3 GIPSY

Precise Point Positioning (PPP) is adopted as GIPSY processing. PPP is a developed technique for analysis of GPS data for precise geodetic purposes Zumberge et al., (1997) . With PPP, the amount of CPU time increases linearly with the number of stations, rather than geometrically as in conventional multi-station analysis. Hence, it is suitable for precise analysis of large numbers of stations like GEONET, or to rapid analysis of a few stations.

On GEONET, PPP uses both IGS precise and rapid GPS orbital and GPS satellite clock estimates from an analysis by six GSI sites around Japan and IGS or broadcast ephemerides. The GPS orbits and clocks are fixed (not estimated) , and the stations are analyzed one at time. The solution files are then merged at the end in order to obtain the final solution file with all the stations in SINEX format.

When both the GPS satellite orbits and GPS satellite clocks are fixed and not estimated, all correlations between stations are zero. This enables us to break the solution up into N smaller estimation runs (N = number of stations) and obtain the identical estimates and covariances for the bias free station positions.

3. 3 Products

Solution files obtained by Bernese, GAMIT/GLOBK , and GIPSY are translated into SINEX format. Since SINEX format files include full covariance matrix, its size is up to 80 MB for each day routine solution except by GIPSY. However, SINEX format is now the same standard format as GPS solution files. Actually, IGS analysis centers submit their solution files in SINEX format. Three major software's can now treat SINEX format, so it is getting easier to combine several SINEX files into one SINEX file using these software's.

3. 4 Output from GEONET

On the display of GEONET, we can look at several kinds of results obtained by routine analysis. This interface is so convenient that users can look at and print out the results only by selecting menus by a mouse. . Figure 9 is the main menu display of GEONET. We can select displacement vector plot map, time series of each component of each observation site, time series of baseline length, and strain map. Currently, displacement vector map and strain map are displayed by appointing observation site name (velocity or strain rate map are not been supported yet) . Figure 10 shows an example output of displacement vector for southwest Japan. Each vector shows displacement from the 15-day-average from Apr. 1～Apr. 15 in 1996 and the 15-day-average from Dec. 17～Dec. 31 in 1996. The reference point is Nita, marked with an asterisk.

Thus, several kinds of figures are easily printed out without special knowledge about GPS analysis.

4 .VELOCITY FIELD OF JAPAN

We can get site velocities by applying a simple least square method to the time series of site coordinates. Hence, we show the example of the time series (Figure 11).

In the vertical plot, significant annual term is observed for all GEONET sites. On the other hand, we see much smaller annual term in horizontal plot. Therefore, we estimated only horizontal site velocities using one-year data for the protection to the annual variation. As to the reference frame, we deploy the kinematic reference frame defined through VLBI analysis (Heki, 1996). According to Heki (1996), the site velocity of Tsukuba is 20.5 mm/yr westward and 2.7 mm/yr southward with respect to the stable region of the Eurasian Plate. We fixed the velocity of Tsukuba to this value. Then, we got the velocity field of Tsukuba to this value. Then, we got the velocity field of Japan using one year data (1996/4/6 - 1997/4/19), and display it in Figure 12.

This result demonstrates various tectonic features. First of all, as the whole, the velocity pattern is significantly different among the southwest Japan (SWJ) and northeast Japan (NEJ). The SWJ is basically moving westward with respect to the Eurasian Plate. This result suggests several possibilities. For example, SWJ belongs to the different plate from the Eurasian Plate, the Amurian Plate (Zonnenshain and Savostin, 1983), which is supposed to move eastward with respect to the Eurasian Plate (Ishibashi, 1983). Other possibility is the local deformation such as upwelling of plume in the Yellow Sea, northwest of Kyushu district (Seno, 1997). The velocity structure changes near the Median Tectonic Line (MTL), and the southern site of MTL moves northwestward with respect to the Eurasian Plate. This reflects the interplate coupling between the Eurasian Plate (here, we suppose this area belongs to the EU) and the Philippines Sea Plate. Tabei et al., (1997) estimated the interplate coupling by using this velocity field, and concludes that the coupling is considerably high on the plate boundary off the Kii Peninsula and Shikoku Island. On the contrary, the velocity of Kyushu Island is more complex. We had three earthquakes during the observing period, and at least two of them, Hyuga-nada-oki earthquakes, have significant postseismic deformation. We are now doing the correction of the co- and post- seismic effects.

The velocity field of the NEJ is also complex. This region is considered to belong to the Okhotsuk Plate, the Pacific Plate, and the Eurasian Plate, so sites of the Pacific coast side have large westward velocity, and others of the Japan Sea coast side have small westward velocity. This implies the interplate coupling between the Okhotsuk Plate and the Pacific Plate. However, the northern part of the Tohoku district shows significantly different aspect; that is, the westward velocity is smaller than other part. This suggests that the interplate coupling is much smaller off this area. This weaker plate coupling is attributed to the 1994 Sanriku Haruka Oki earthquake. Heki et al. (1997) analyzed the long-term post-seismic deformation of the earthquake (Figure 13). We suppose that even after the long term after slip, the interplate coupling has not been recovered. This is one of the healing process of large earthquake occurs on plate boundaries (rupture -> relaxation -> decoupling -> coupling). Hokkaido shows more complicated aspect along the southwest coast, like as the Pacific side of Tohoku district, interplate coupling is observed and the norm of velocity vector gets smaller in the central Hokkaido. However, in the southwestern coast, westward motion becomes larger again. One speculation for this is the viscoelastic effect of the Hokkaido-Nansei-Oki earthquake, occurred in July, 1992. Compared to such complex crustal deformation in the southern Hokkaido, the northern Hokkaido does not reveal any significant deformation. This region may be a relatively stable region of the Okhotsuk Plate.

Like above, we divided Japan into SWJ and NEJ. The boundary between these two regions is considered to be a plate boundary. Traditionally, the Itoigawa-Shizuoka Tectonic Line (ISTL) has been the most possible candidate as the plate boundary. As an anti-these, Tada (1983) proposed a new boundary, which runs from Shizuoka to not Itoigawa but Niigata by analyzing triangulation data. Our velocity field supports his result (Figure 14). Therefore, as long as we look at crustal surveying data, plate boundary runs eastward of the Sado Island.

5. CONCLUSION

GEONET is a powerful system both to monitor spatial temporal crustal deformation and to serve as an active controlling system for GPS surveying.

Three major powerful software's are available for this system. And, crustal displacement velocity field has been obtained.

GEONET deploys more than 900 permanent observation sites. The density of observation sites will be higher than that of the first order triangulation points. Therefore, this system is expected to serve as the backbone survey network of Japan.

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Figure 1 The antenna station pillar at Umaji (Kochi pref) .

Figure 2 The central body of the tower.

Figure 3 The data analysis center at GSI in Tsukuba.

Figure 4 Directory Structure.

Figure 5 Clustering strategy for New network by BERNESE.

Figure 6 The back-bone cluster of Trimble site network used in Bernese daily processing.

Figure 7 An example of regional Trimble cluster.

Figure 8 Ashtech cluster

Figure 9 The Main Menu display of the new GSI's GPS the system.

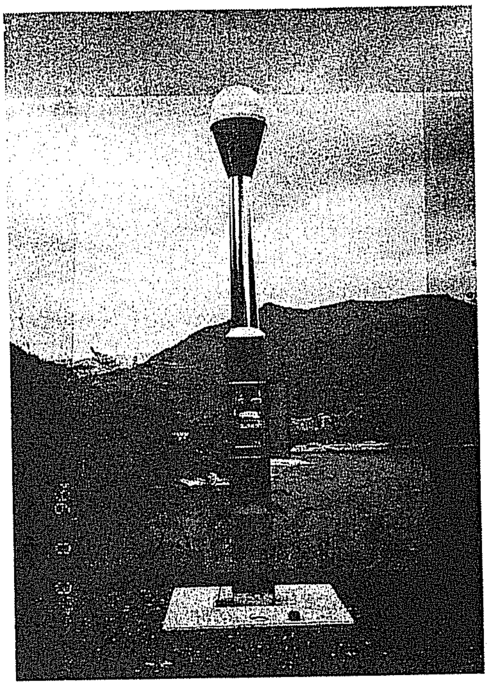
Figure 10 Example output of displacement vector.

Figure 11 An example of time series of site coordinates

Figure 12 Horizontal displacement velocity field of Japan derived from one-year continuous GPS data (Apr.6, 1996 – Apr.19, 1997)

Figure 13 Long term post-seismic deformation following 1994 Sanriku Haruka Oki earthquake (after Heki et al., 1997)

Figure 14 Horizontal crustal deformation of the central part of Honshu Island. (Observation period: Oct.1, 1996 – Jun.14, 1997, dot line shows the proposed plate boundary, solid lines show active faults.)



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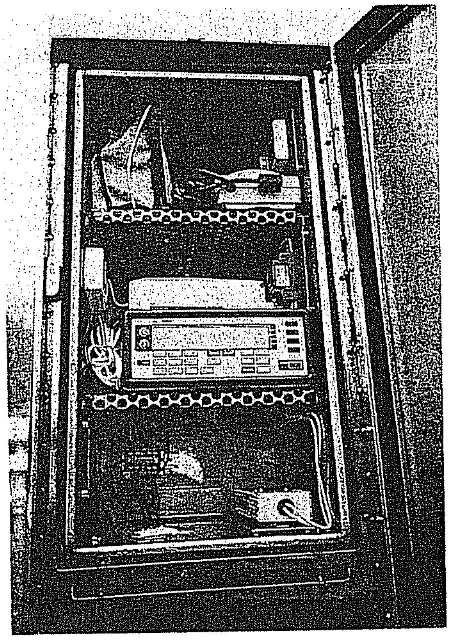


Figure 2 The central body of the tower.

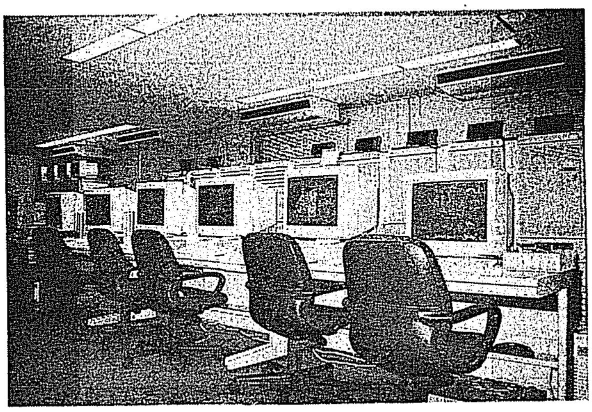
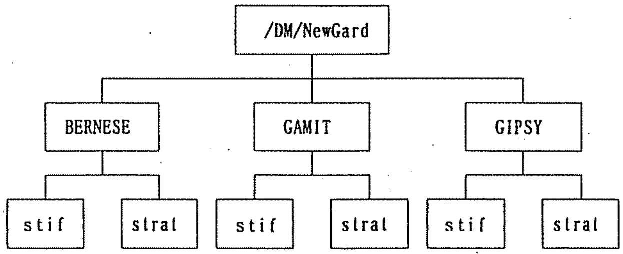


Figure 3 The data analysis center at GSI in Tsukuba.



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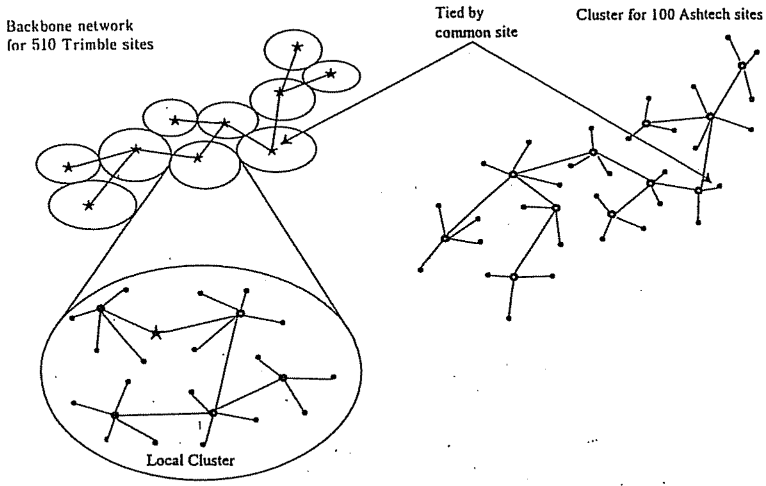


Figure 5 Clustering strategy for New network by BERNESE.

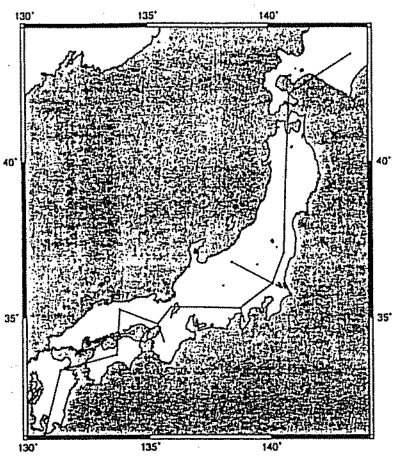


Figure 6 The back-bone cluster of Trimble site network used in Bernese daily processing.

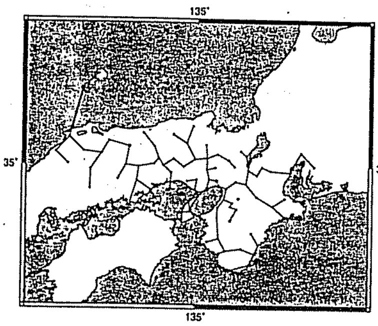


Figure 7 An example of regional Trimble cluster.

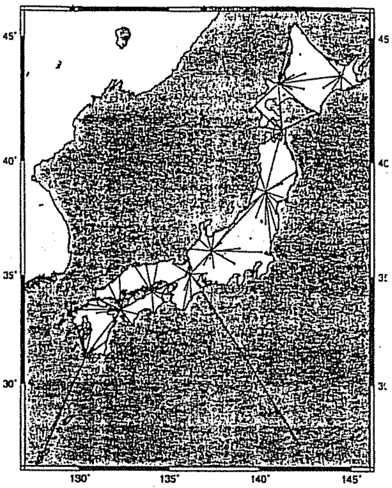
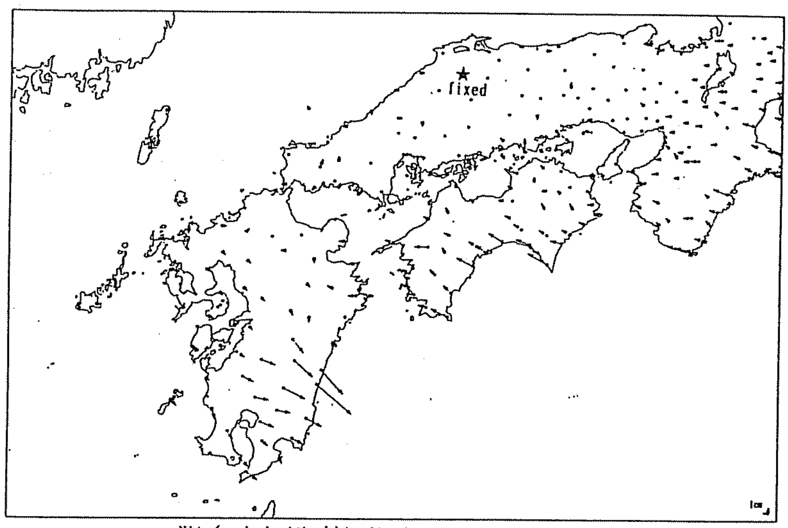


Figure 8 Ashtech cluster

Figure 9 The Main Menu display of the new GSI's GPS the system.



Nita(marked with ★)is fixed.
data used are Apr. 1～Apr. 15 and Dec. 17～Dec. 31 in 1996

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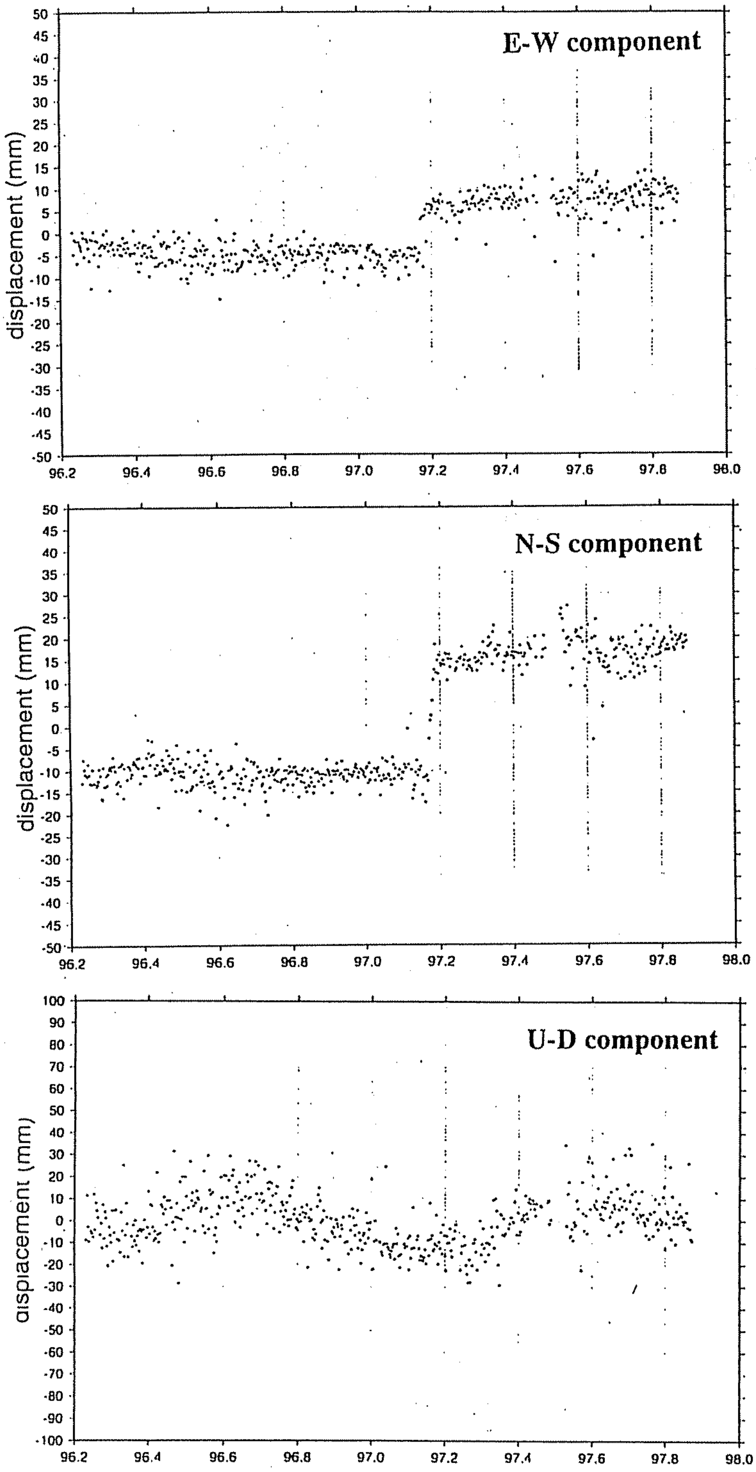


Figure 11 An example of time series of site coordinates

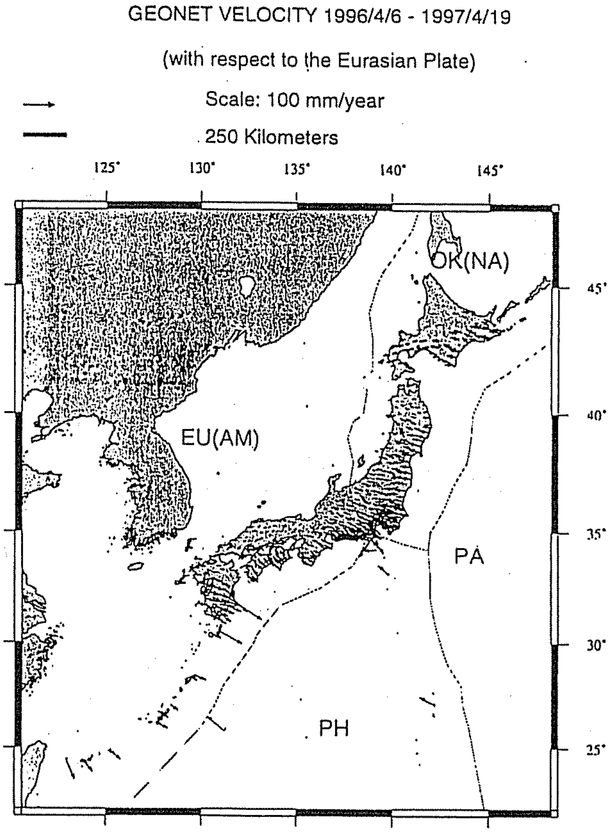


Figure 12 Horizontal displacement velocity field of Japan derived from one-year continuous GPS data (Apr.6, 1996 – Apr.19, 1997)

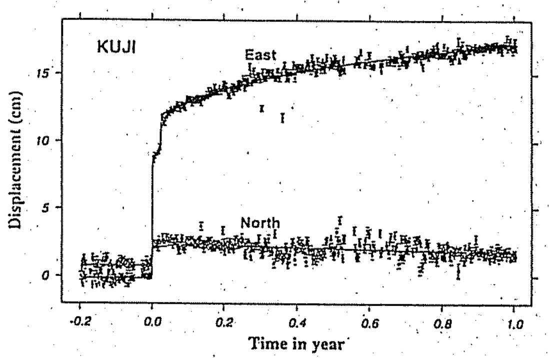
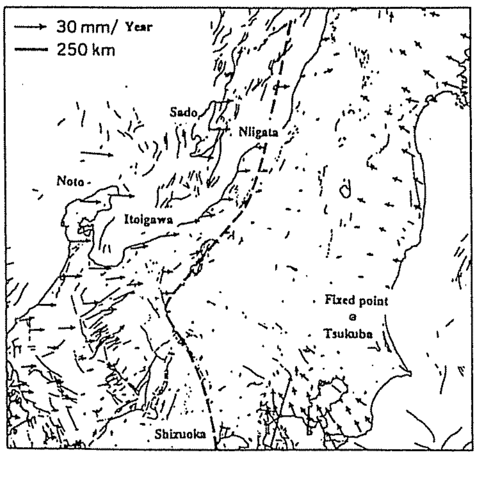


Figure 13 Long term post-seismic deformation following 1994 Sanriku Haruka Oki earthquake (after Heki et al., 1997)



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