Crustal deformations in the Japanese islands observed with the nationwide continuous GPS observation system

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Abstract

The Japanese nationwide continuous GPS observation network has been established in October 1994. There are 215 permanent GPS station all over Japanese islands. The observation data have processed in two way. One is real time, on-line processing with the broadcast ephemeris and other is off-line processing with the precise ephemeris. Some interesting results have been obtained since the beginning of the observation. GPS network has revealed with astonishing rapidity crustal deformations, such as associated with destructive earthquakes and tectonic plate motion. These results shows the excellent performance of the permanent type GPS network, although only one year observation.

Introduction

The Japanese islands locate at the plate boundary between the oceanic plate and the continental plate, such as the Pacific plate, the Philippine Sea plate and the Eurasia plate. Therefore, the steady state crustal deformation due to plate motion is large. In addition, destructive earthquakes have occurred frequently and the crustal deformation associated with those earthquakes have observed.

Geographical Survey Institute(GSI) has set the nation wide continuous GPS observation stations about 200 since October 1994. There were three large magnitude earthquakes in the past one year in and around the Japanese islands. We would like to report the crustal deformations associated with those earthquakes and also steady state crustal deformation obtained by the GPS network.

Global Positioning System(GPS)

Global Positioning System(GPS) is a new surveying technique applying space technology designed by the United States

Department of Defense(DoD). GPS is a satellite dependent navigation system. GPS consists of 24 satellites in six orbital planes, each having four satellites. The satellites operate in circular 26600 km orbits at an inclination of 55 degrees with 0.5 sidereal day period. The system has been fully operated since July, 1993.

GPS is higher accuracy than that of EDM. Especially, interferometric GPS can achieve 0.1-0.01 ppm level relative precision. In addition this high accuracy, GPS has the following characters,

1) three dimensional positioning,
2) no requirement of intervisibility between the observation points,
3) all weather condition,
4) 24-hour operation,
5) short observation time,
6) easy data processing,
7) availability of automatic real time, on line observation, and
8) handy instrumentation and high portability.

Role of Geographical Survey Institute

The Geographical Survey Institute(GSI) is the major governmental organization for surveying and mapping in Japan, and carries out the basic surveying and mapping of Japan and the associated research connected with them. One of the most important task of GSI is establishment and maintenance of the national geodetic control points, such as the triangulation station and the bench mark. GSI initiated a nationwide triangulation survey using theodolites in 1883 and the nationwide triangulation network consisting of 6000 control points was established in 1911. Re-surveys of these control points contribute to the monitoring of crustal movements.

According to the national program for earthquake prediction, GSI carried out the monitoring the crustal movements by the precise geodetic distance survey with Electromagnetic Distance Meter(EDM) in 1974. The first cycle measurement of 3000 primary control points was completed by 1983. The second cycle started in 1984 and completed by 1994, and GPS was used from 1990 changing to EDM.

Nationwide GPS Network in Japan

GSI installed four GPS receiver in March 1987. This is the first time of the introduction of GPS to Japan. Since then, GSI intensive experimental observations had carried out under the many conditions. In March 1988, a total of several tens of GPS receivers further introduced to universities and governmental institutes related to the earthquake prediction project. Those receivers are used for the monitoring of crustal deformation by campaign type observation. However, the biggest advantage of GPS observation is on-line, real time remote control ability at permanent stations.
Compared to repetition of campaign type GPS observation, continuous observation at permanent GPS stations can achieve at the highest accuracy and temporal resolution.

In February 1990, the Crustal Dynamics Department(CDD) of GSI established 3 permanent GPS stations in the Izu peninsula, 150 km southwest of Tokyo, in order to monitor crustal deformation associated with volcanic swarm earthquake activity.
In March 1991, another permanent GPS network ,consisting of 4 receivers, was established around Unzen volcano, Kyusyu, west Japan, which has been erupting since November 1990. Moreover, in March 1992, CDD established a permanent GPS network in the Suruga bay region, central Japan, where is considered to be the seismic source region of the coming Tokai Earthquake. And CDD began a continuous GPS observation at the Iriomote island, located western margin of the Ryukyu arc, in December 1992.

We could achieved a high precision, sub-cm precision for about 10 km baseline, and obtained some significant results concerning to the crustal deformation associated with earthquake and volcanic activities through these small GPS network experiences.

On the basis of success in monitoring of crustal deformation by the permanent type observation of GPS, a new project of establishing a wide and dense GPS network in the Kanto-Tokai region was proposed by CDD in April 1993.

Kanto and Tokai region, central Japan, are designated as “Areas for intensified observation for earthquake prediction” by the

Coordinating Committee for Earthquake Prediction(CCEP). This project intends to establish a GPS monitoring network in order to observe precursory crustal deformation preceding earthquake generation and volcano eruption. CDD named this new network COSMOS-G2(COntinuous Strain MOnitoring System with GPS by GSI). The COSMOS-G2 network consists of 110 permanent type GPS stations. Fig.1 shows the COSMOS-G2 network. We designed the COSMOS-G2 network as densely as possible. Average spacing between GPS stations is 10 -15 km. Actually, the number and the density of stations of the COSMOS-G2 network is the first of its kind in the world. The COSMOS-G2 project was adopted in the supplementary budget of Japanese government in FY 1993. The COSMOS-G2 network came into operation in March 1994.

On the other hand, Geodetic Department(GD) of GSI proposed a permanent type GPS network covered all over Japan, behind CDD one year. The aims of this project are, to establish a new 3-dimensional geodetic network instead of the conventional one, and to monitor tectonic movement in the Japanese Islands. This new network was named GRAPES(GPS Regional Array for Precise Surveying and Physical Earth Science).

Fortunately, GRAPES was adopted in the second supplementary budget of Japanese government in FY 1993 and established in October 1994. Fig.2 shows the GRAPES network. GRAPES has 104 GPS stations in all over Japan and its average spacing is l00-120 km.

Thus, we have two GPS sub-networks in Japan. Both sub-network have a similar system. A GPS antenna is equipped on the top of a 5 m stainless pillar with a 2 m firm ground base(Phot.1). The antenna is covered with a radome. A receiver, a modem, and a battery are kept inside of the pillar. A brass maker is attached to each station for site preservation. The data collected at each station are transferred to data centers at GSI by a high speed modem through a public telephone line.

Currently, the data from each sub-network are processed independently with its own strategy. Since the COSMOS-G2 requires a quick turnaround of the results for the real time monitoring, a broadcast ephemeris is used with Bernese Processing

Engine and the observation window is set to be 12 hours. On the hands, GRAPES requires the highest precision to detect tectonic movements in an over 100 km scale. Thus, 24 hour data are off-line processed with a precise ephemeris from the International GPS Service for Geodynamics(IGS) using the GAMIT software.

In response to the recent sequence of destructive earthquakes, GSI plans to expand the number of stations up to 640 in March 1996 as shown in Fig.3 and the current two sub-networks will be integrated into one new system, a nationwide GPS network. Furthermore, the total number of GPS stations will be expand up to about 1000 in the end of 1996. With these expansion, the Japanese islands will be covered by a dense GPS network with the average spacing of about 20 km. The Japanese nationwide GPS network is the largest and most dense permanent GPS network in the world.

Kurile Islands Earthquake(M=8.1)

The nationwide GPS network became operational from September 27,1994. On October 4, 1994, i.e., 1 week after the operation, a large earthquake, which earthquake magnitude M=8.1, hit the northern part of Hokkaido, and the southwestern part of the Kurile islands. It is well known as the 1994 Kurile islands earthquake. The epicenter was about 200 km east off the Nemuro peninsula in Hokkaido, but the eastern part of Hokkaido strongly shook with JIVIA seismic intensity 5. It was afraid that the station pillars of GPS tilted by the strong shaking. The stability of the pillar at Nemuro on site was checked and it was concluded that there were no problems in the pillar. Thus, all GPS stations survived the shaking and provided us continuous observation data of the quake. A preliminary result on the coseismic crustal deformation was reported to the public on October 6, 1994, proving the quickness of continuous GPS network in monitoring crustal deformation. It needs 2-3 years to obtain the same result by the conventional method.

Because all stations in Hokkaido could be displaced from the earthquake, it was assumed that the Usuda station, Honshu, Japan was the fixed point in the analysis. Usuda is located about 1100 km southwest of the epicenter, so it is considered that the coseismic displacement at the Usuda station is negligible small.

Twenty-four-hour data from GPS stations in Hokkaido and Usuda with a one-minute interval are processed for two-week period from September 27 to October 12, one week before and one week after the earthquake. For the base line processing, it was used the GAMIT software with National Geodetic Survey(NGS) precise ephemerides and earth rotation parameters from International Earth Rotation Service(IERS) Bulletin. Tropospheric delays are estimated at each station in every 3-hour period.

Fig.4 shows a graphic representation of the horizontal crustal displacement vectors associated with the 1994 Kurile islands earthquake in Hokkaido. The nearest station to the epicenter, Nemuro, 170 km west of the epicenter, moved 44 cm to east and 10 cm to down. Since the fixed station is so far from the epicenter, the displacement can be regarded as absolute value. Two possible fault models have been proposed based on this crustal deformation. Because of poor resolution of determination of aftershock hypocenters and lack of information of crustal deformation in the near field, it is impossible to distinguish which model is better.

Fig.5 shows the time series of the coordinates at Nemuro before and after the earthquake. Error bar shows twice of the standard deviation. Offset after the main shock in October, 4(day of year 277) are evident in the time series. It is obvious that there are no significant changes in site coordinates for a week before and after the earthquake.

1994 Off Sanriku Earthquake(M=7.5)

On December 29, 1994, a large earthquake with magnitude of 7.5 occurred at far off Sanriku, northeastern Honshu, Japan. Strong shaking of the JMA seismic intensity 6 was recorded at Hachinohe city. There are no damage at the GPS stations and the crustal deformation associated with the earthquake was successfully detected.

Fig.6 shows the horizontal crustal displacements at each GPS station analyzed by above mentioned data processing. The Kuji station, northern part of Tohoku, about 200 km far from the epicenter, moved up to 8 cm toward to the epicenter and subsided up to 2 cm. The crustal deformations associated with the quake was not so large but a large after effect crustal deformation was observed. Fig.7 shows a time series of dally change in Kuji-Rifu baseline components for about 8 month. A exponential function type post seismic relaxation was recorded at the Kuji station where was nearest station to the epicenter. The relaxation time constant is estimated to be about 60 days. It is considered that this phenomenon is either due to the creep motion of the fault plane or due to the visco-elastic character in the upper mantle. Fig.6 gives a strong impression of superiority of the continuous GPS observation.

The off Sanriku earthquake is understood to be a thrust type faulting occurred at the plate boundary between the Pacific and the Okhotsk plates.

1995 event in the Izu peninsula

Since 1978, earthquake swarm and anomalous crustal deformation have frequently occurred in the northeastern Izu peninsula. It is considered that these anomalous crustal activity is caused by magma intrusion into the uppermost crust. In fact,, a submarine volcanic eruption occurred at east off of Ito city in 1989. CDD has carried out the continuous GPS monitoring in the eastern Izu peninsula since February 1990. In September 11, 1995, An earthquake swarm began to activate at near Ito city. At the same time, a crustal extension was observed with COSMOS-G2. Fig.8 shows an example of the daily distance change between HTS and KMR across the swarm region. A crustal extension correlate to seismic activity has been detected successfully. The monitoring of crustal deformation with COSMOS-G2 has played important role to judge the change in seismic activity, especially the time of cease-activity.

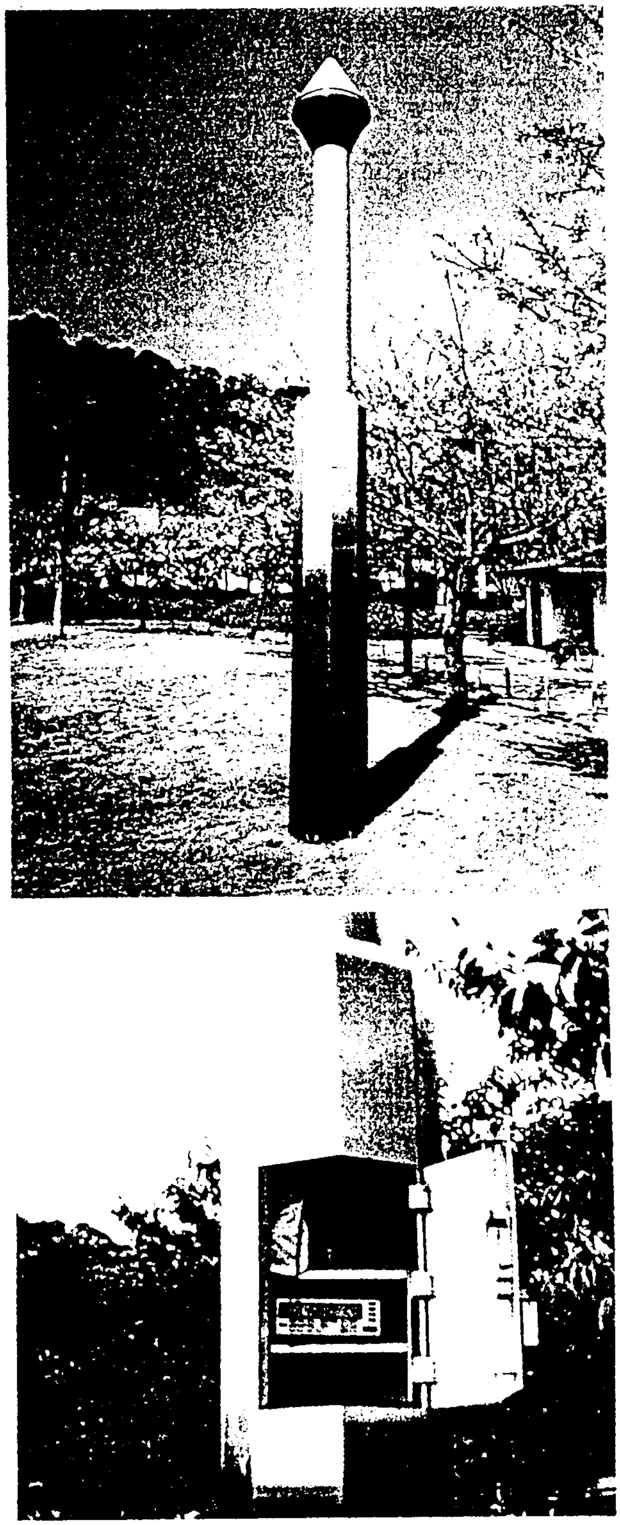
Steady state crustal deformation

So the Japanese islands situate at an active plate boundary, that the crustal strain rate is high as much as 0.2-0.3 ppm/year. But the precision of EDM is low as 1 ppm, then it needs 10-20 years to observe an effective crustal deformation. Indeed, we needed 15 years to obtain the result which is shown in Fig.9. GPS, on the contrary, is high precision, so we can make the period short. It took 2-3 years to obtain a effective result by the campaign type GPS observation, but it took only half year to obtain a similar result to Fig.9 with the continuous GPS observation. Fig.10 shows a horizontal displacement vectors in the western Japan which was obtained with the observation of GRAPES during 6 months.

Conclusive remarks

The nationwide continuous GPS network is better than conventional geodetic techniques in many ways. The maturity of GPS technology, represented by the state-of-the-art hard&softwares and precise ephemerides, allows few-mm horizontal precision.

These factors make the nationwide GPS network into an ideal tool for understanding of dynamics in the earth's interior.



Phot.1 Station pillar and electronic device of COSMOS-G2 and GRAPES. The antenna is equipped on the top of a 5 m stainless steel pillar with a firm ground base. A receiver, modem and a battery are kept inside of the pillar.
A commercial electronic power line and public telephone line are used for the driving power and the data transmission.

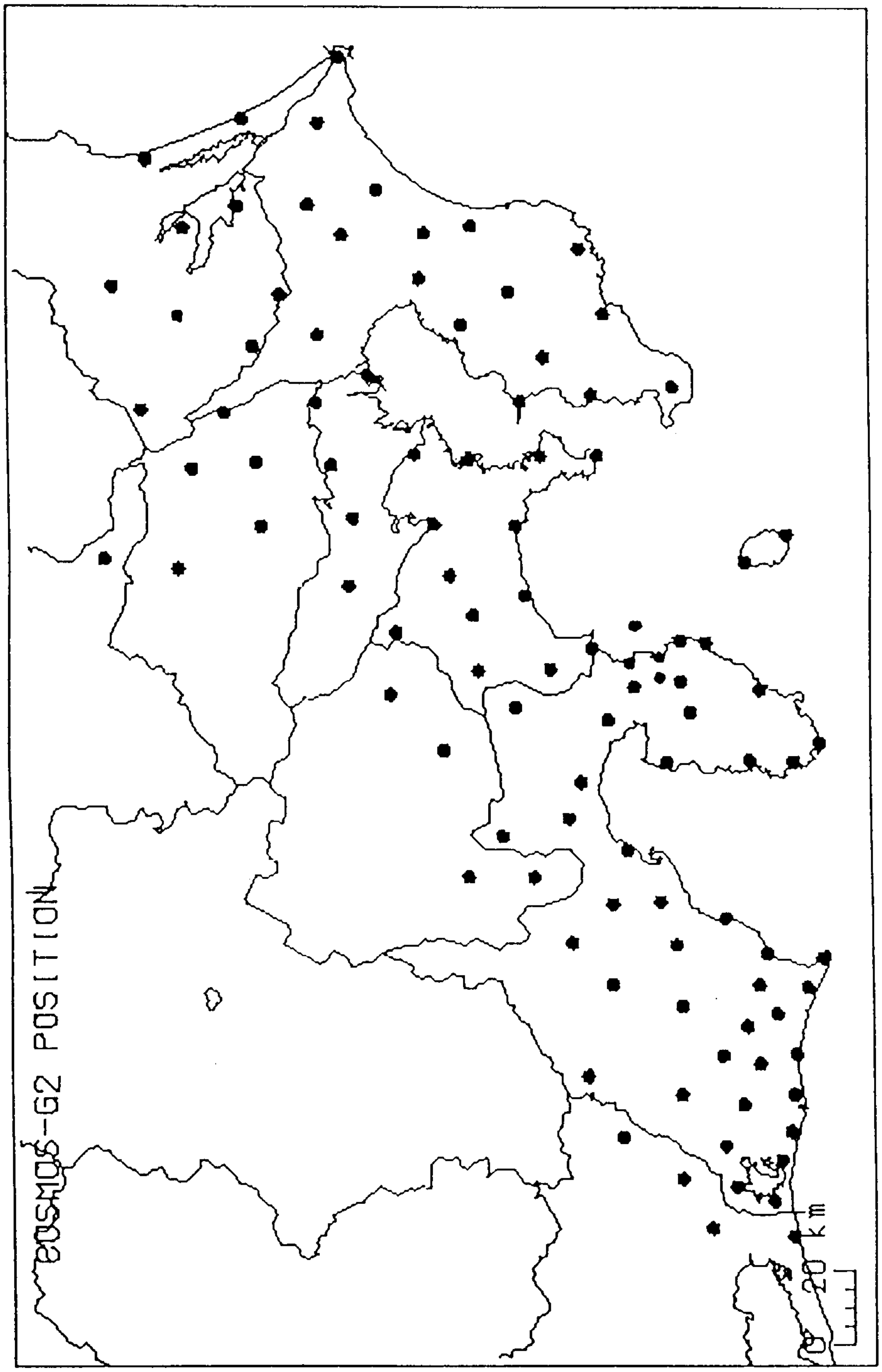


Fig.1 COSMOS-G2 network.

Fig.2 Present day GRAPES network(October 1995).

The Grapes

GPS Regional Array for PrEcise Surveying
(and Physical Earth Science)

will appear in April 1996
with 620 stations.
covers whole Japan
with 25 km interval.

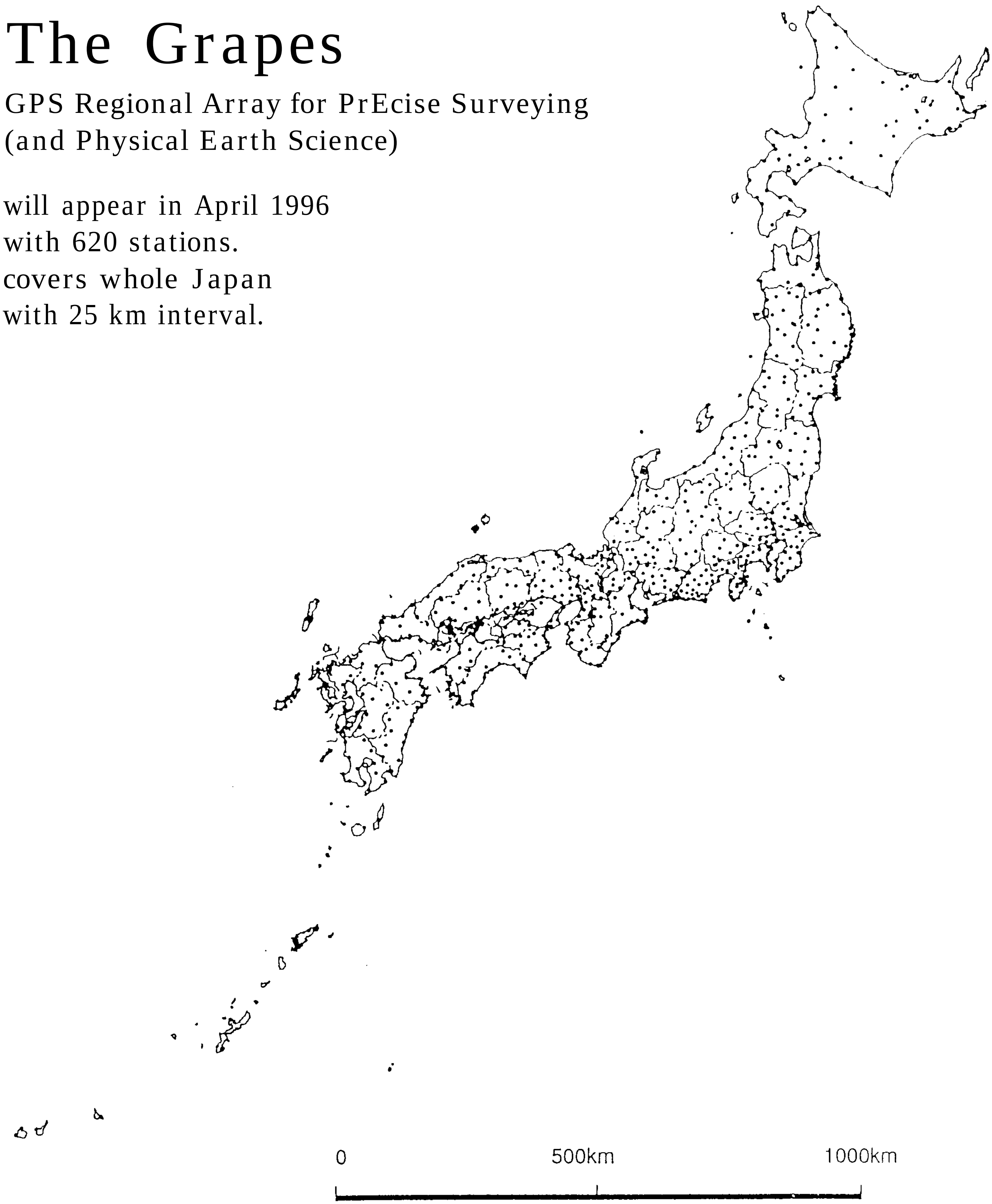


Fig.3 Feature GRAPES network (March 1996).

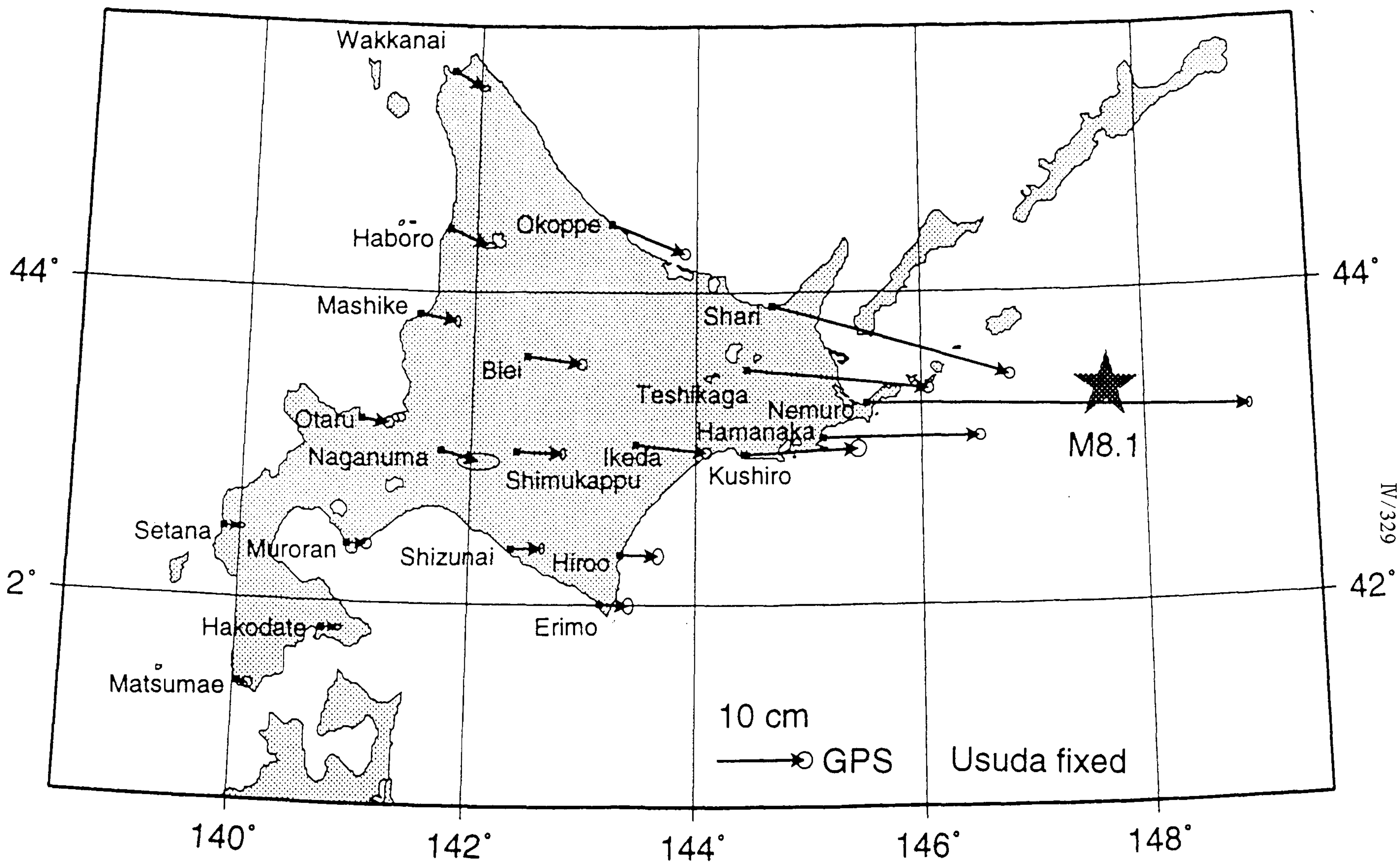


Fig.4 Horizontal crustal displacement vectors associated with the 1994 Kurile earthquake.

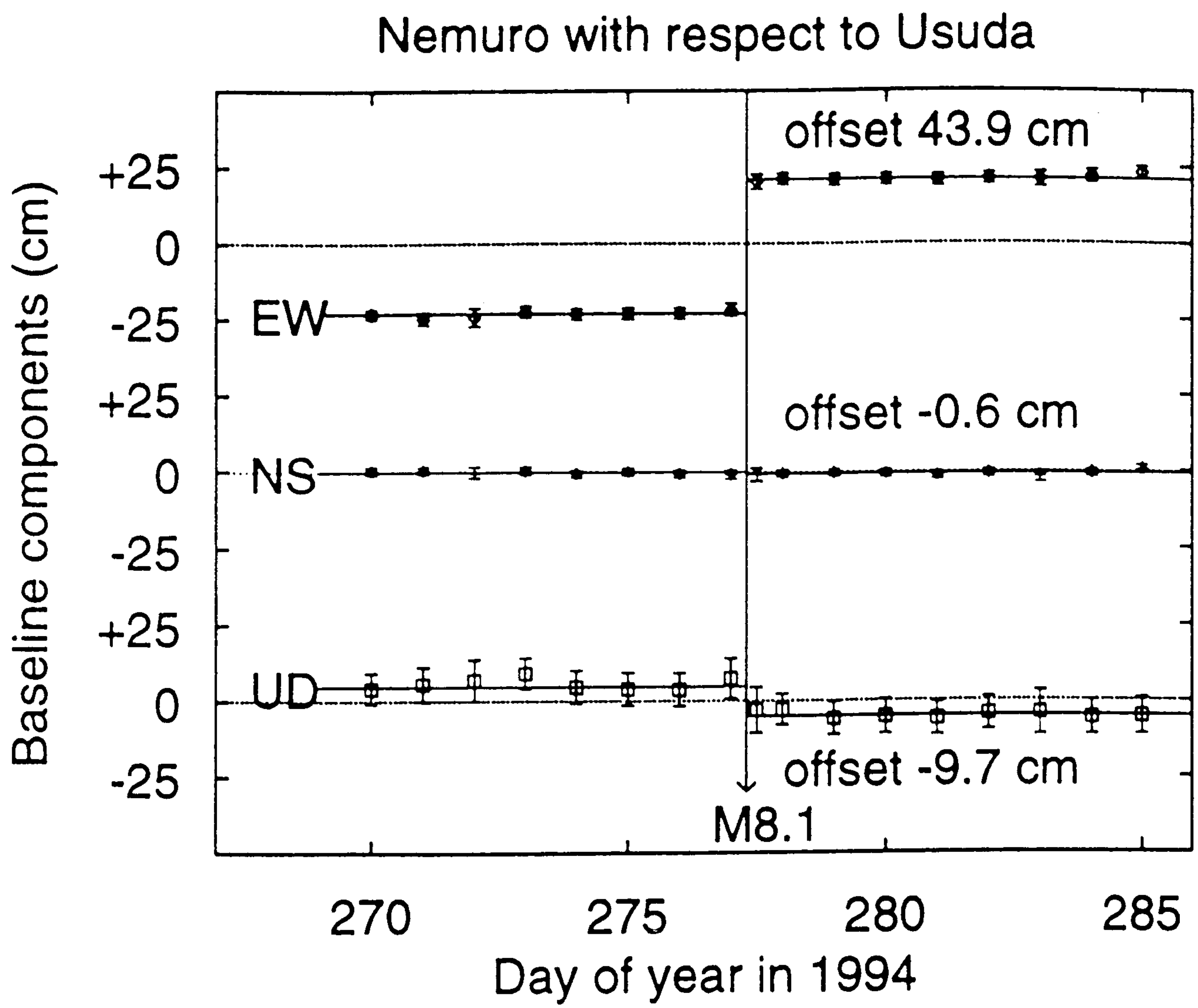


Fig.5 Daily change in position coordinates at Nemuro.

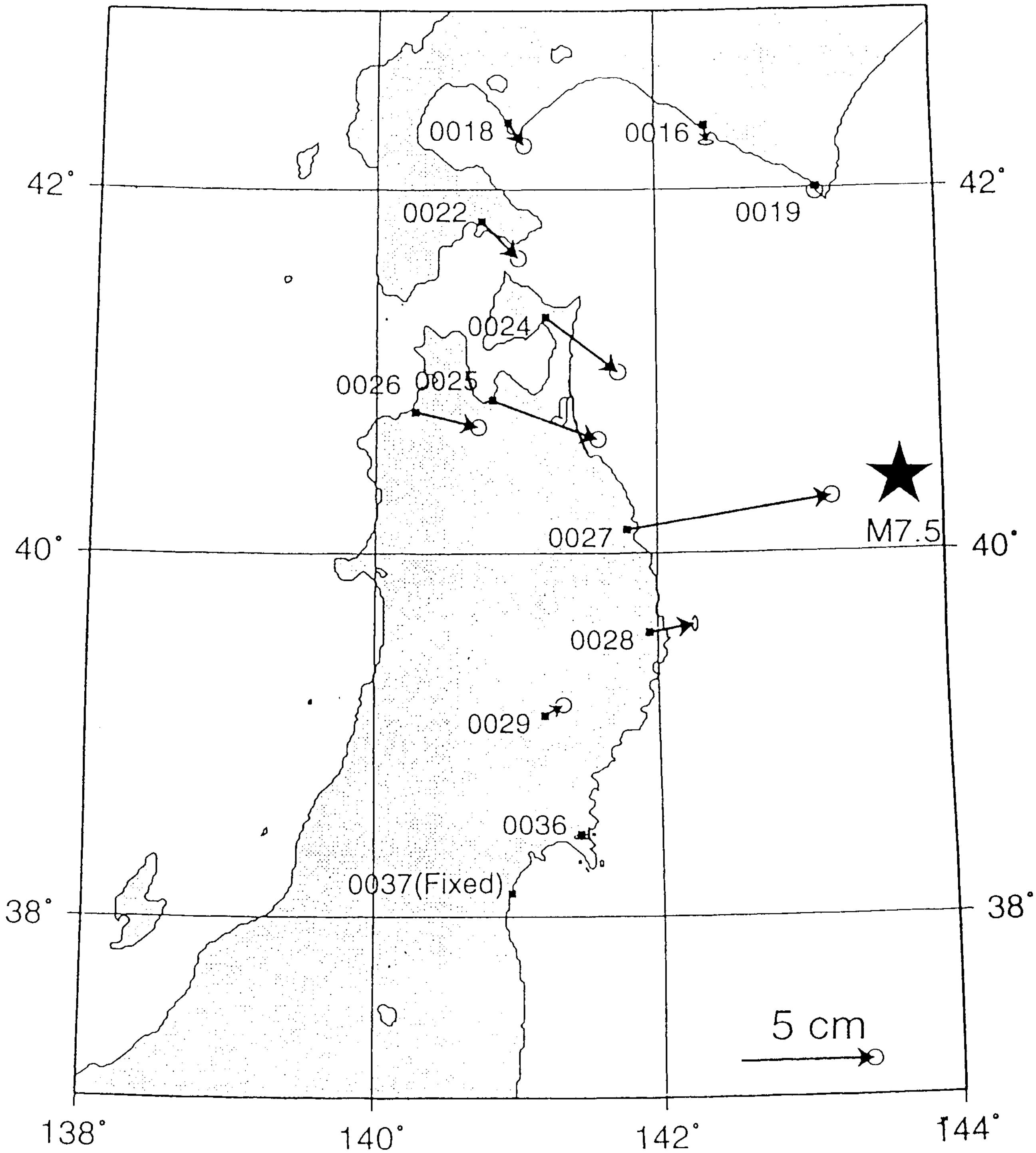


Fig.6 Horizontal crustal displacement vectors associated with the Off Sanriku earthquake.

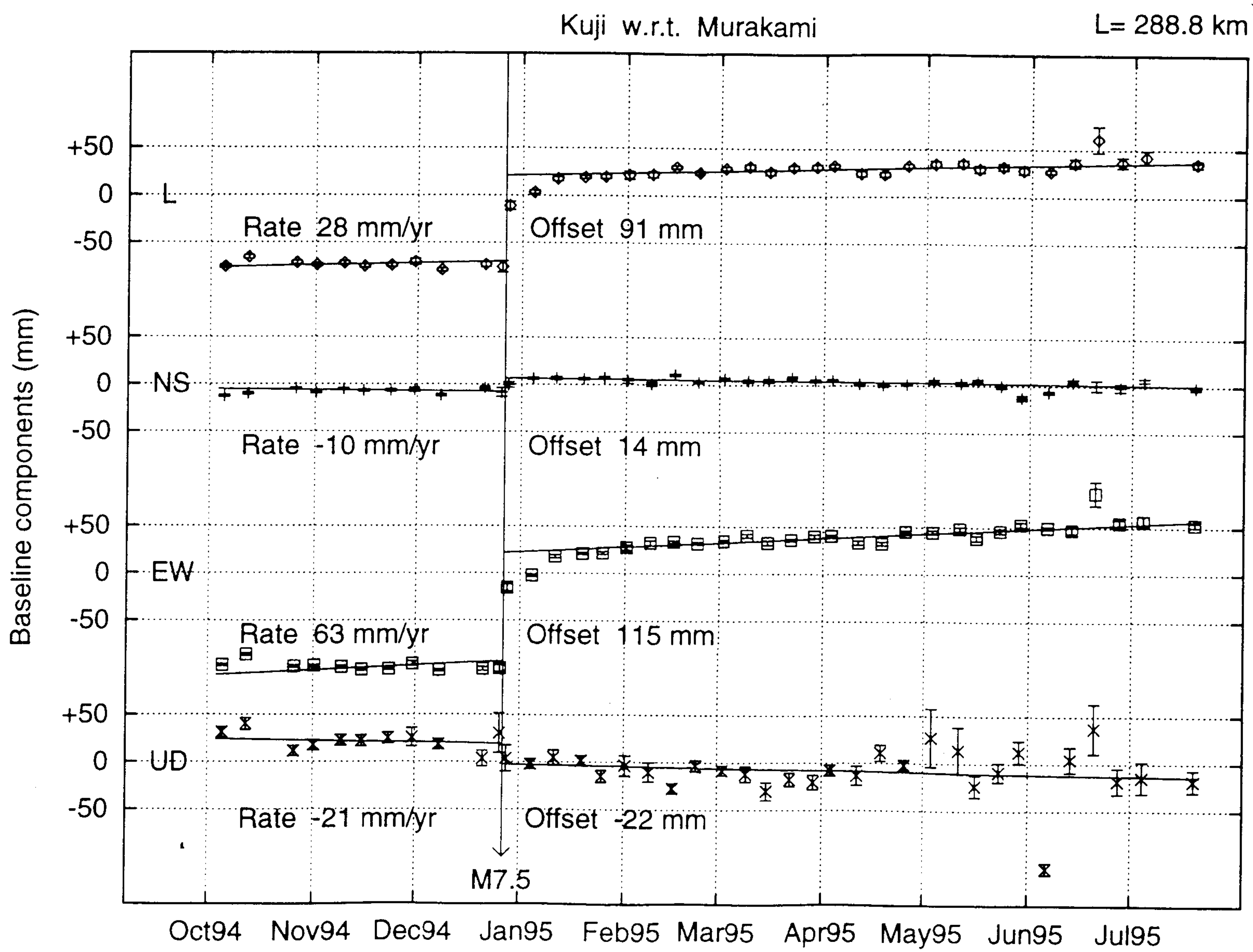


Fig.7 Daily change in position coordinate at Kuji. Note a exponential function type slow change in the E-W component.

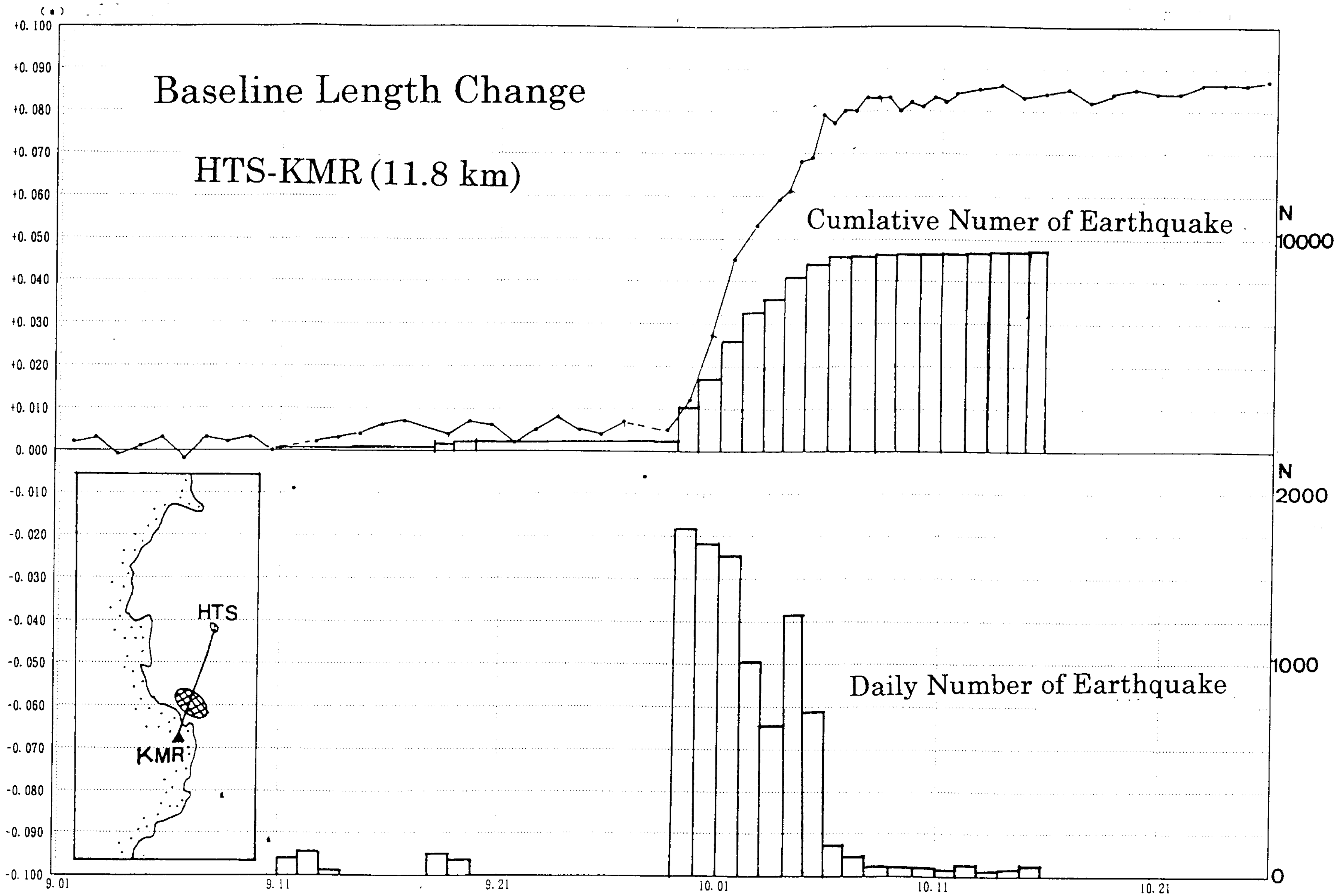


Fig.8 Daily change in distance between HTS and KMR, and daily number of earthquake. Note a high precision GPS measurement and a relation between the distance change and the earthquake occurrence.

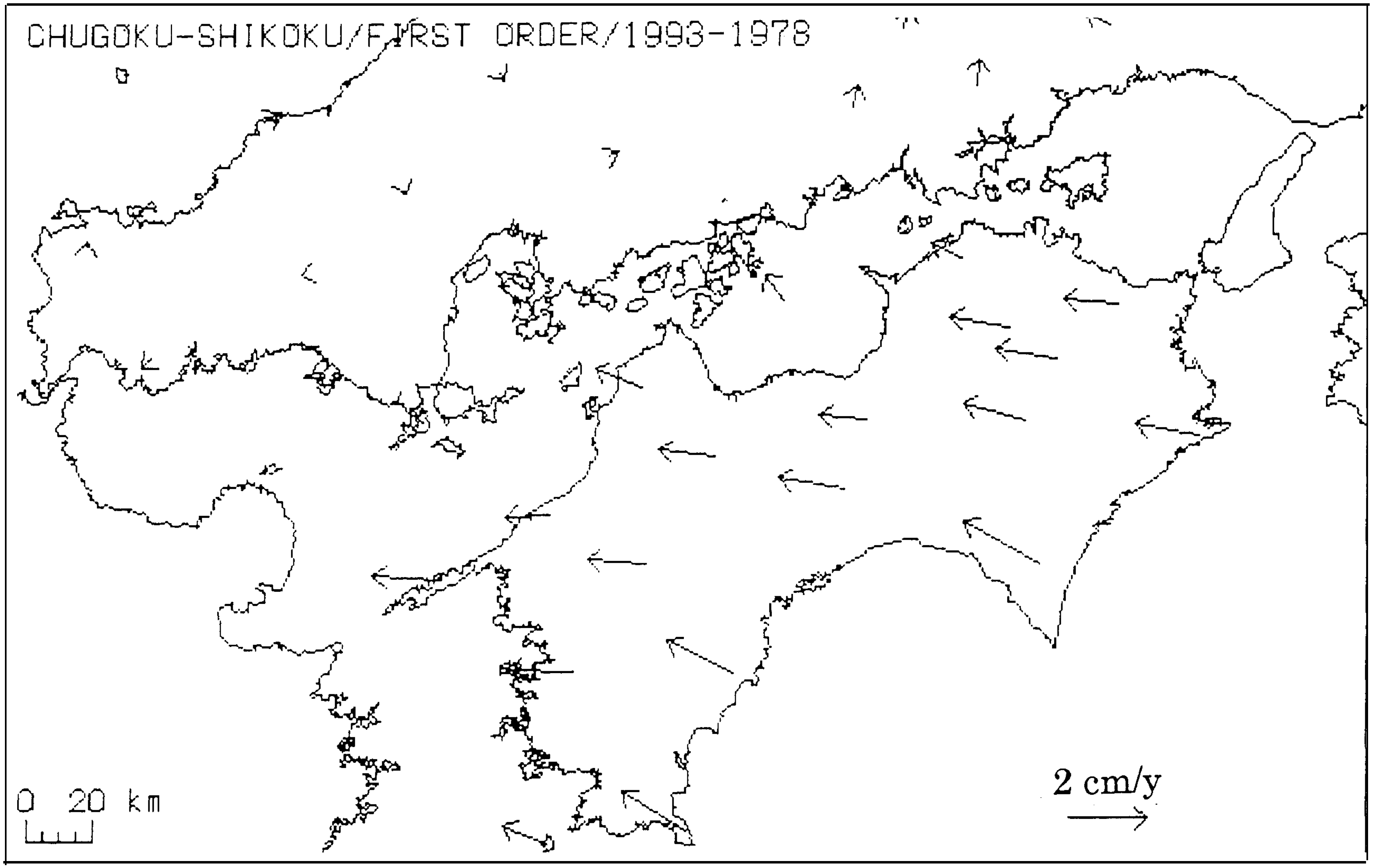


Fig.9 Horizontal crustal displacement vectors due to the subduction of the Philippine Sea Plate in the Sikoku district obtained with the conventional surveying method(EDM). It took 15

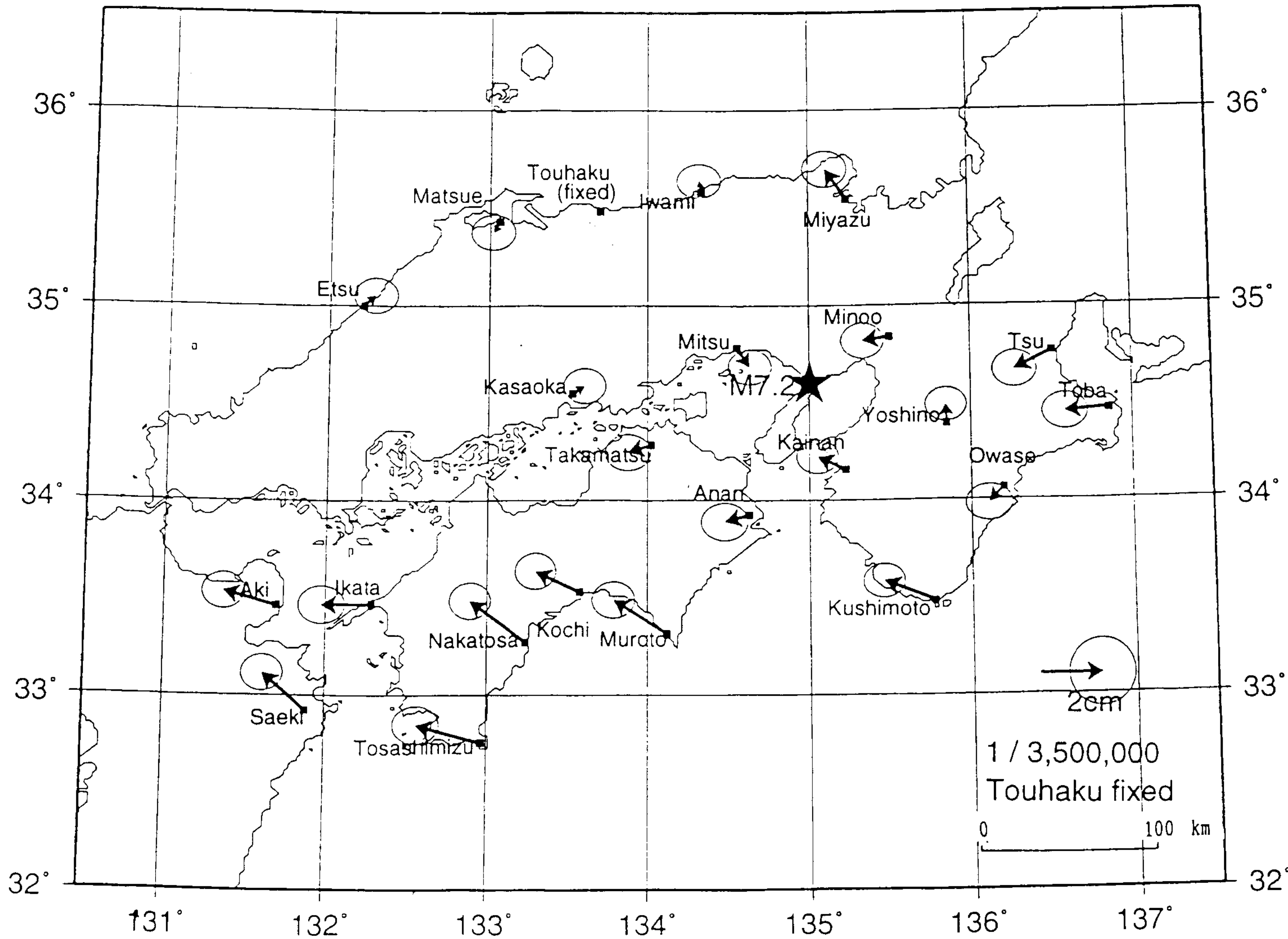


Fig.10 Horizontal crustal displacement vectors due to the subduction of the Philippine Sea Plate in the western Japan obtained with GRAPES. It took only 6 months to obtain the result.