Observed Vertical Motion of Kozu-Jima Island Using Interferometric GPS*

Diana Polonska*1, Masatoshi Harigae*1, Toshiaki Tsujii*1, Masaski Murata*1, Fumiaki Kimata*2

Abstract

The main purpose of propossed calculations of GPS interferometry data was to determine the vertical mutual motion of Shizuoka and Kozu-Jima sites, located in volcaninally and tectonically active zones. The most significant behavior of selected baseline vectors in the large motion of their vertical components, which for the first time demonstrates major shifts of the upper layers of the earth's crust taking place not only in case of inter-seismic and postseismic deformation activities but under ordinary seismic circumstances as well. Distinguishing between obtained results and tide gauge data would allow us to assess the compatibility of these two methods and to form a geoscientific approach for qualitative conclusion of observed phenomena.

要　旨

GPS搬送波位相干渉法により静岡及び神津島の位置座標を計算し，火山活動やプレート運動によって非常に活動的なこれら地点の垂直方向の運動について解析した。その結果，これらの局が地震中及び地震後のみならず, 平時でも垂直方向に運動していることが明らかとなった。また, この結果はタイドゲージのデータ処理結果ともよく一致している。

1. Introduction

The determination of mutual motion of GPS observation stations has been described in several places. The experimental apparatus for this kind of investigation embodies deployed GPS receivers array continuously recording signals from GPS satellites, which allows to obtain spatial coordinations of observed sites with high resolution using appropriate processing software. Using this tool for monitoring crustal deformations in Japan and worldwide as a rule authors used only active faults and plate tectonics explanations of detected occurrences, ignoring possible local motions of earth crust within the limits of “stable” plates themselves.

Kozu-Jima island belongs to East Izu monogenetic volcano group, an area which is one of the most tectonically active regions in Japan, and its crustal motion has drawn a special attention. For monitoring, GPS receivers have been placed in the proximity of this island. In this paper authors demonstrate the importance of introducing subdivision of representative areas on morphotectonic mesoblocks using structural geomorphologic analysis for fuller picture of observed phenomena.

2. Data Analysis

The following sets of locations were used for circumscribed investigation: Usuda, Kozu-Jima and Shizuoka for calculations of GPS interferometry data; Kozu-Jima, Yaizu, Shimizu-

* 平成8年9月27日 受付(recieved 27 September 1996)
*1 Control Systems Division
*2 University of Nagoya

minato, Minamiizu for analyzing tide gauge data.

Main purpose of proposed calculations of Interferometric GPS data was to determine if appropriate the vertical mutual motion of above-mentioned sites. In order to obtain sufficient volume of data for reliable statistics group of daily solutions has been made after processing relevant Receiver-Independent Exchange (RINEX) format files. In static mode, GAMIT software was utilized to process a daily batch of data. Using Usuda station as stable fixed site (because its coordinates have been adjusted in the ITRF93 determined by VLBI with cm accuracy) we have calculated time series of latitude, longitude and height for three stations over the five periods in 1995 and 1996 years. The daily average solutions of coordinates for Kozu-Jima and Shizuoka were under loose constraints relative to Usuda.

It is necessary to mention that 0 height mark for particular location is situated on the surface of mathematical model of referring ellipsoid. GPS data reflect geoid related information due to the direct dependence of satellites' orbits on earth gravitational field (presuming that other errors like tropospheric delays of signal, problems with a fixed site, etc. eliminated) while tide gauge data directly related to predetermined sea level for certain place. Hence the question of compatibility for two methods comes into view. Indeed, determination of geoid boundaries and sea level surface for particular area involves a wealth of issues in numerical modelling, hydro-physics, coastal area dynamics and other oceanographic disciplines with no common consent in this matter.

Relative errors in height for GPS-related measurements based on GAMIT precise ephemerides are two orders more explicit than similar tide gauge-related errors. It means that statistics received from calculations of GPS data should be more accurate and reliable by definition.

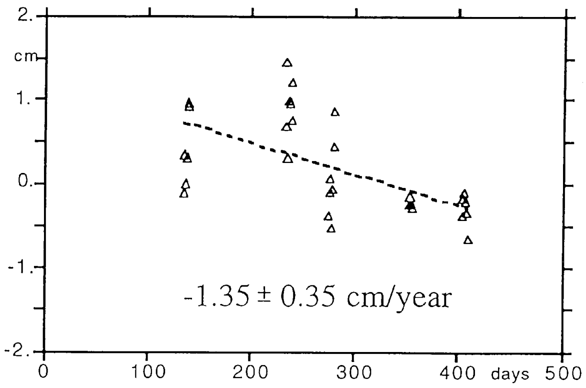

Fig. 2a. Latitude change between Kozu-Jima and Shizuoka estimated by GPS

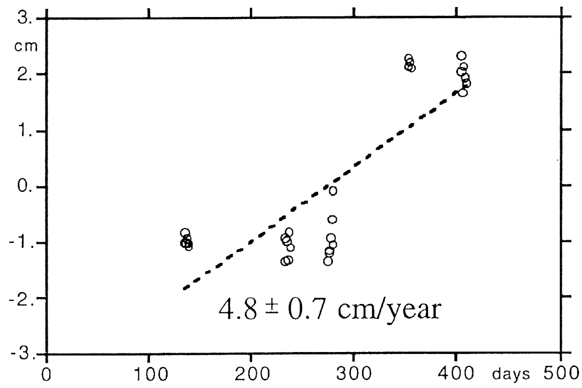

Fig. 2b. Longitude change between Kozu-Jima and Shizuoka estimated by GPS

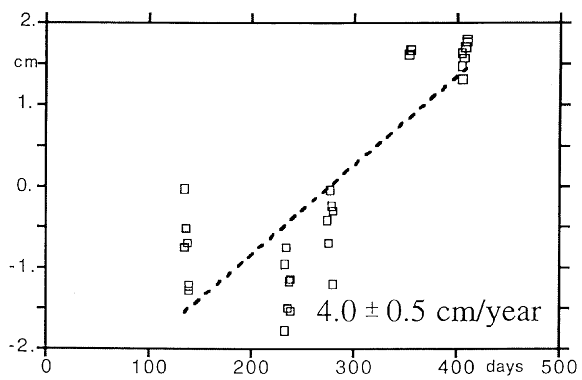

Fig. 2c. Baseline length change between Kozu-Jima and Shizuoka estimated by GPS

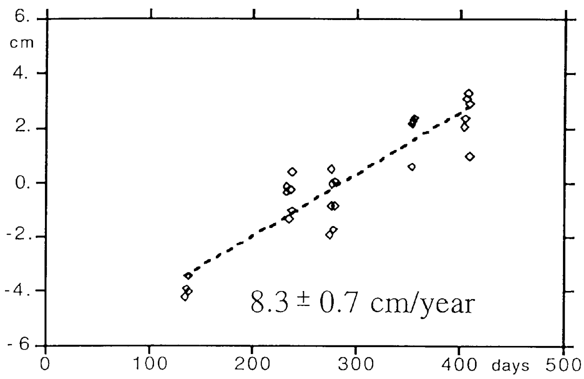

Fig. 1. Height difference between Kozu-Jima and Shizuoka estimated by GPS

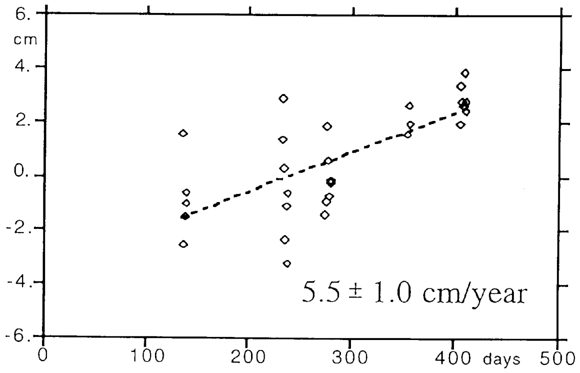

Fig. 3. Height difference between Kozu-Jima and Shizuoka estimated by GPS

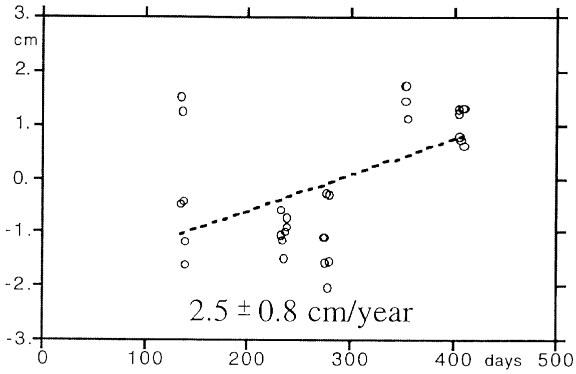

Fig. 4b. Longitude change between Kozu-Jima and Shizuoka estimated by GPS

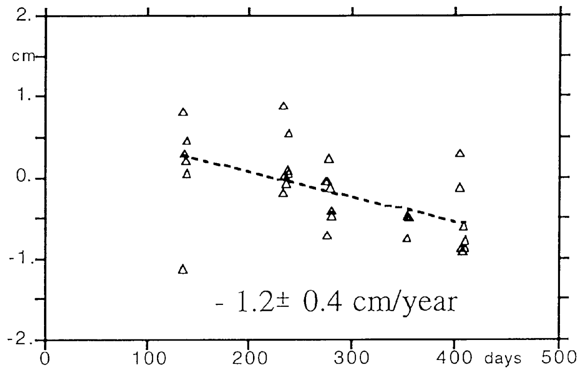

Fig. 4a. Latitude change between Kozu-Jima and Shizuoka estimated by GPS

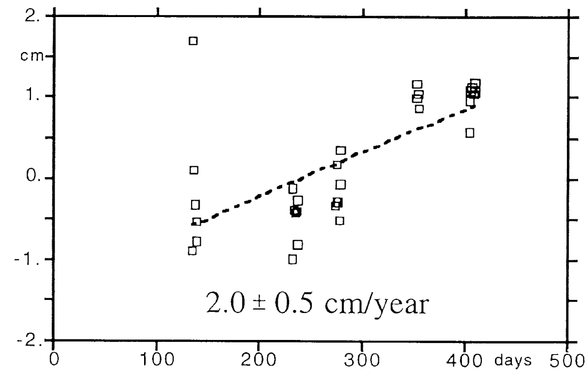

Fig. 4c. Baseline length change between Kozu-Jima and Shizuoka estimated by GPS

Collection of precise positions enabled us to obtain component of length for baseline vectors Kozu-Jima-Shizuoka, Kozu-Jima-Usuda and Shizuoka-Usuda. On presented graphs (Figure 1-7) each point of baseline vector coordinates denotes the result of one day solution. Best-fit regression lines were obtained by least-squares method.

3. Results

We obtained time series of 31 independent determinations of stations positions over the period from 14 May 1995 to 13 February 1996. Most impressive occurrence in behavior of selected baseline vectors lies in significant motion of theirs vertical components. Indeed, after correlation was made among three specified vectors (Figures 1-6) the following outlines can be scetched:

Kozu-Jima is most intensively moving site with eastward drift in the longitudinal component with a velocity of about 25 mm／year, north shift of 12 mm／year and astonishing upward movement with vertical velocity of about 55 mm／year (everything relative to fixed Usuda site).

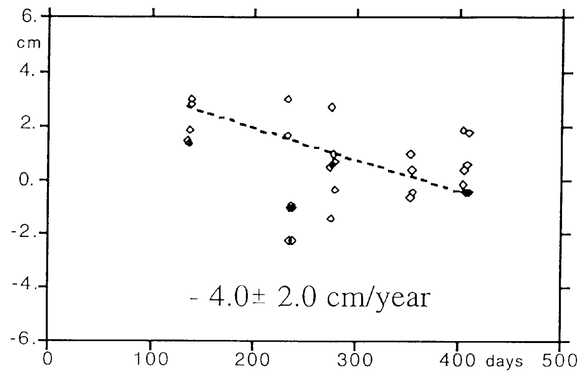

Fig. 5. Height difference between Shizuoka and Usuda estimated by GPS

Motion of Shizuoka along longitudinal component has similar velocity 25 mm／year as in previous case with invert direction. Also invert comparative with Kozu-Jima's radial part

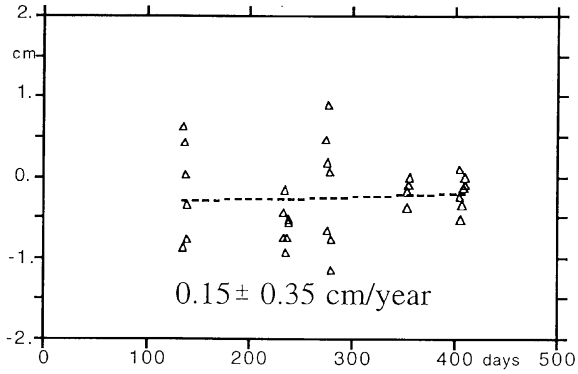

Fig. 6a. Latitude change between Shizuoka and Usuda estimated by GPS

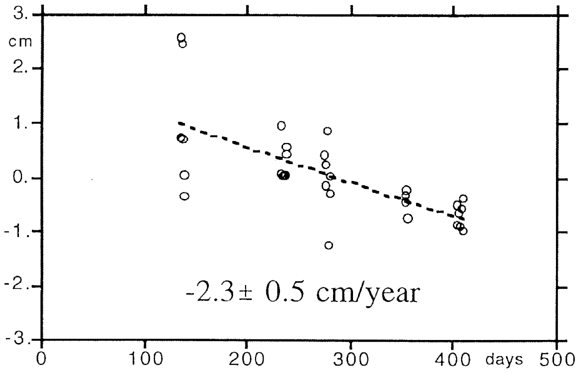

Fig. 6b. Longitude change between Shizuoka and Usuda estimated by GPS

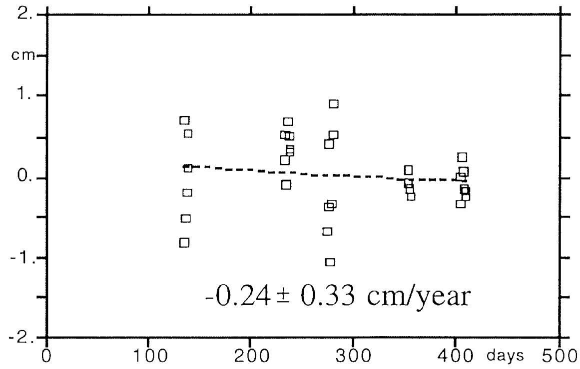

Fig. 6c. Baseline length change between Shizuoka and Usuda estimated by GPS

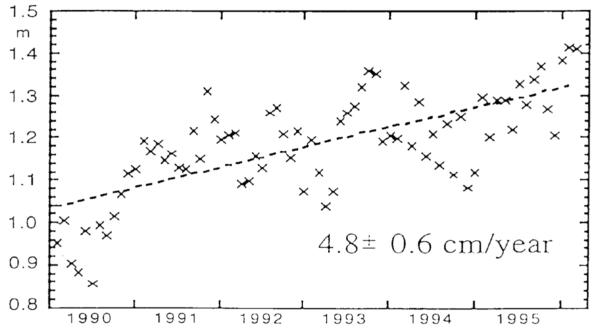

Fig. 7a. Time-dependent height difference between the tide gauge stations Kozu-Jima and Minami-Izu

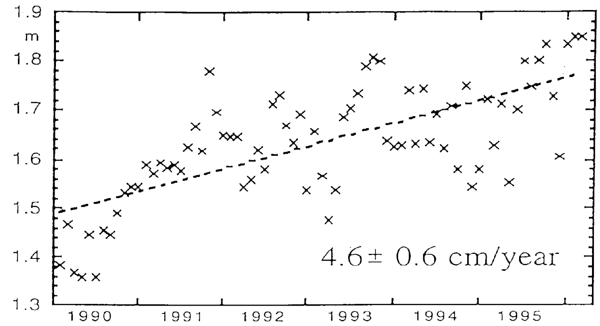

Fig. 7b. Time-dependent height difference between the tide gauge stations Kozu-Jima and Yaizu

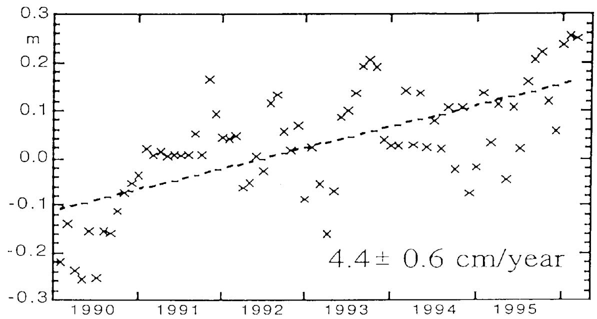

Fig. 7c. Time-dependent height difference between the tide gauge stations Kozu-Jima and Shimizu-minato

motion has velocity of about 40 mm／year downward. Within the data obtained baseline length remains virtually invariant for terrestrially located Shizuoka and Usuda GPS stations.

High rate of change in height difference between Kozu-Jima and Shizuoka (Figure 1) derived to be 8-9 cm／year was compared to 4-5 cm／year inferred from tide gauge data of Yaizu, Shimizu-minato, Minamiizu and Kozu-Jima. Both rates agree qualitatively and the reason for mismatch could be attributed to error in GPS coordinate solutions and error in the rates from tide gauge data. On the other hand, almost invariant result for three tide gauge stations in relation to Kozu-Jima site (Figure 7) shows unexpectedly high correlation and thus proves relevance of this method with long period statistics available for verifying of Interferometric GPS measurements.

In particular, as selected tide gauge data are affected essentially because of rapid ocean current of the Kuro-Shio streaming near the Kozu-Jima and the tide gauge stations have been placed in the shores, considerably apart from GPS stations, tide gauge rates of change in height could differ to some extent from true rates of the points of GPS stations. Moreover, as it was proposed by Dr. Polonska, this mismatch could occur in case if relevant sites of observations locate in morphotectonically different areas (morphotectonic mesoblocks) or on their borders.

4. Interpreting The Results in Geomorphic Context

To analyze the latter option Morphotectonical

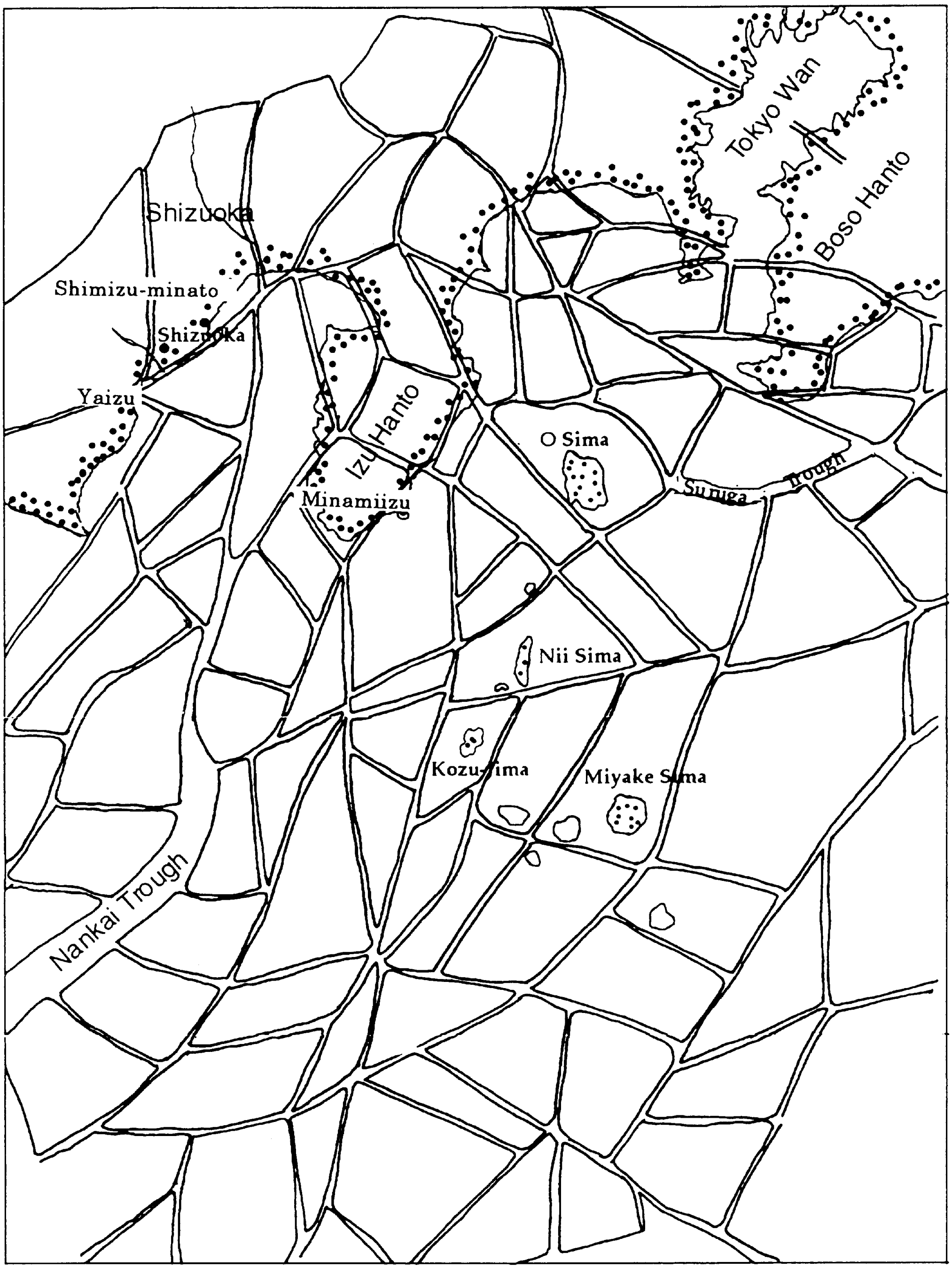

Fig. 8. Morphotectonic Introductory Subdivision of The Areas Within the Northern Edge of The Philippine Sea Plate.

Analysis (see Appendix) as geomorphic approach was applied [Polonska, 1991]. A series of morpho-metric maps was created and compiled in order to delimit mega- and mesoblocks for questionable territory. The Bathymetric Chart of Central Nippon (1 : 1 000 000, compiled from the various sources of the Hidrographic Department, M.S.A. Japan to 1981) was of service for this work. Set for analysis included the following maps: map of the submarine valley network; map of absolute heights of the blocks' tops surfaces; map of tectomorphoisohypsas; slope angles map. This allowed us to create the map of morphotectonical blocks of the northern part of the Philippine Sea plate (Figure 8).

From tectonical viewpoint this area, considered to be the northern edge of the Philippine Sea plate (PH), is quite complex because of the triple junction of Eurasian (EUR), PH, and Pacific (PA) plates. PAC plate is subducting underneath EUR and PH, while the PH plate is subducting beneath the EUR plate. Consequently, the PH plate contacts the EUR along the Nankai-Suruga and Sagami troughs, and the leading edge of the PH plate subducting from the Sagami through probably contacts the subducting PA plate at depth less than 100 km [*Nakamura et al.*, 1984 ; *Ishida & Hasemi*, 1988].

The plate boundary between the PH and EUR plates around the Izu block, first outlined by *Sugimura* [1972] with the concept of collision at the northern side of the Izu block, has been discussed geologically and geophysically. The basic structure of the plate boundary characterized by the subduction along the Suruga and Sagami troughs and the collision at the northernmost part of the Izu block between both throughs.

Several models have been proposed for the understanding of these activities in relation to the Collision Tectonics. As long as geological features of collision are still open for discussions here we made our first attempt to give explanation involving mentioned above methodology. It has already proven its efficiency in regions with high neotectonic activity like Mexico, Chilean Andes, Baikal area, Bulgarian seacoast and shelf. Applying this approach in present study the introductory map of morphotectonical blocks has been created.

Our analysis shows, following reference of *Yonekura* [1983; 1989], that subduction of the PH plate is well represented in the submarine landforms and geological structure along the continental margin. Even preliminary geomorphologic analysis of Kozu-Jima island with proximate area noticeably revealed block structure of the region. Vault-boulded character of movement for mega- and mesoblocks was authenticated after collating the map of absolute heights of the blocks' tops surfaces with the map of tectomorphoisohypsas (resulted from the hypsometric map by the graphoanalytic techniques). During this procedure it was found that the borders between different blocks are expressed by both the steep slopes and gradual transition in different cases.

After comparison of the bathymetric and slope angles maps had been made the boundaries of regional combinations of the slopes of different steepness (which can be treated as measure of intensity of tectonic and erosion processes) coincide well with closed tectomorphoisohypsas.

PH and EUR plates with the plate boundaries between the Sagami and Suruga throughs strongly relate mutually. Because stress is continuous across collision zones the sharp plate boundary can not be expected between Sagami and Sugura throughs, and the strain due to convergence of the plates is accomodated by their internal deformation, [*e. g. Somerwille* , 1979].

The compressional stress field induces interplate deformation of the weak crust such as active reverse or strike-slip faulting and active folding, both of which are commonly observed in this tectonic territory. According to *Ida* [1991] the interplate deformation caused by the seismo-volcanic processes is participating in separating the plate without producing any discontinuity of material on the surface lithosphere. Accepting this idea the author suggested that several zones subjected to a strong extensional force associated with the tearing of the plate like eastern to Izu block and the belt of monogenetic volcanoes, which was generated under an extensional stress field [*Nakamura*, 1986 ; *Ida*, 1991].

As a result these strengths and tensions naturally reflect on the blocks of different ranks. Consequently each block should be moving with its own velocity and direction to compensate divergent tensions induced in tectonic field.

For example, block with Kozu-Jima island substantially moves upwards and eastward relatively Shizuoka's block with respectively 8 cm／year and 5 cm／year. These figures are self-explanatory for static GPS experiments. They normally detect one order lower movements for superior plates [*Murata*, 1993]. Furthermore, suchlike horizontal shifts seems to be not temporally homogeneous according to *Kimata et.al.* [1995].

Until now numerous authors refer to estimations made by *Seno* [1977] and *Minster* and *Jordan* [1979] showing 3-5 cm／year North-Western movement of PH, which does not coincide at all with detected movement of Kozu-Jima's block. Its significant deposition under ordinary seismic circumstances is the result of mutual vertical movement between relevant morphotectonic mesoblocks, which include Kozu-Jima and Shizuoka sites. Vertical movement is superior to the displacements caused by situating of these two stations on different tectonic plates : PH and EUR. Kozu-Jima's latitudinal shift relative to both Usuda and Shizuoka has the same value, which agrees with observed mutual stability of two terrestrially located stations for east-west and baseline vector length components. On the other hand, nautically located Kozu-Jima slightly moves northward while being a part of the Philippine Sea Plate. This horizontal movement has one order lower velocity comparing to vertical one resulting from mesoblock structure of the region

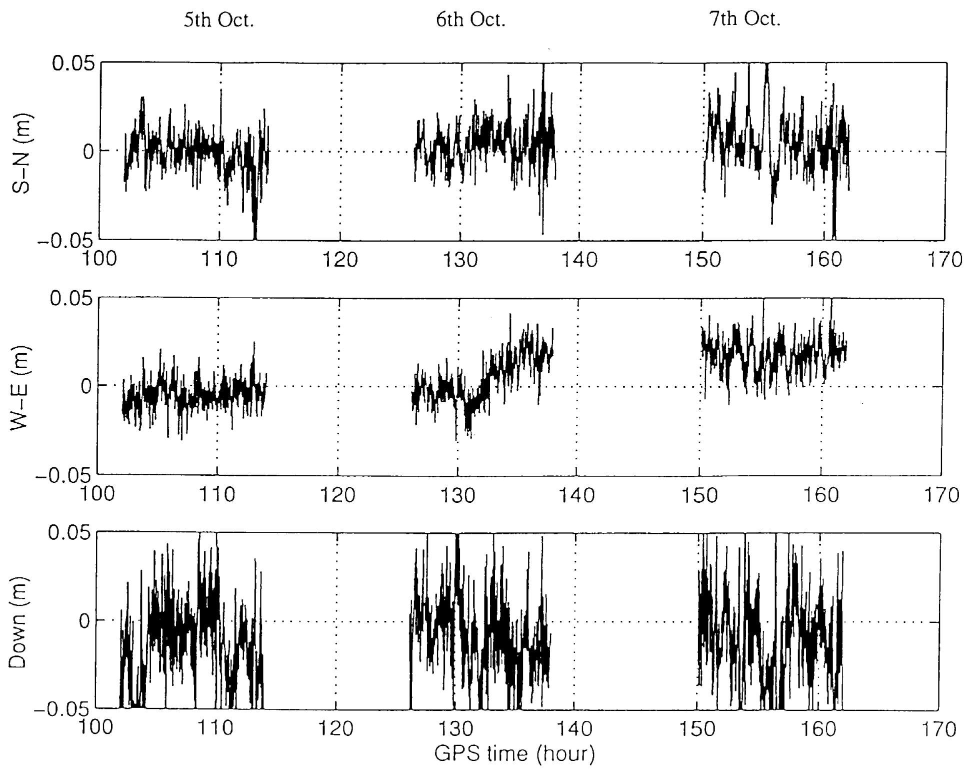

Fig. 9. Change of the baseline vector from Kozu-Jima to Nii-Jima before and afrer the Earthquake on 6th Oct. '95 calucutated by Kinematic GPS

The future study of this issue will lead us to better understanding of the interplate crustal deformations. They affect four types of tectonic activities. The major earthquakes like 1974 Izu-hanto-oki earthquake of magnitude 6.9 which released only a minor part of the relative plate motion. Next two types are represented by earthquakes swarms; volcanic (July 89 earthquake swarm was accompanied by a submarine eruption which generated a new volcanic crater - Teisi Knoll) and nonvolcanic [*Ida*, 1991]. Fourth tectonic events are aseismic, mainly crustal uplift. Crustal deformations of such kind should reflect magmatic processes and transport in the deep lithosphere, which is one of important problems in the region.

5. Kinematic GPS results

In kinematic mode, three baseline vectors of Kozu-Jima relative to Shizuoka, Minami-Izu and Nii-Jima were determined by two bandwidths phase measurement with a time resolution of 60 seconds. Baseline lengths are 106.7, 56.7 and 22.1km respectively. Analysis software used was that created at NAL for real-time kinematic GPS for aircraft navigation. For baseline Kozu-Jima and Shizuoka, ambiguities could not be resolved correctly due to baseline length being longer than 100 km, while for baselines from Kozu-Jima to Minami-Izu and Nii - Jima, ambiguities were accurately fixed and horizontal movement of Kozu-Jima due to the earthquake occurred on 6th October, 1995, was detected clearly (Figure 9). This shows that real-time kinematic GPS could be applied for monitoring local area crustal deformation.

6. Discussion

We face intensive vertical mutual movement for Kozu-Jima and Shizuoka sites according to the data of GPS interferometry. This result for the first time demonstrates that weighty shifts of upper layers of earth crust take place not necessarily in case of inter-seismic and postseismic deformation activities.

Defined morphotectonical mesoblocks of Kozu-Jima island with proximities showed us nonhomogenious character of area's geomorphic structure. Even rough assessment displays that we are concerned with energies of the same order as devastating ones, involved during the earthquakes, under ordinary seismic situation.

In view of promising perspectives of using Kinematic GPS techniques on local scales (～20 km) applying of this tool for serviceable earthquake prediction seems to be meaningful for areas with highly evolved morphotectonic structures.

Considering the current state of interpretations of Static GPS data, to be more precise serious limits in processing workstations capabilities to cover wide range of sites and not fully adequate from geomorphic point of view approach in choosing locations of most of the GPS stations (in school campuses and public parks) authors confident that taking into account block structure of the populated territories would contribute in high extent for prevention of natural catastrophes in addition to existing methods and that it is imperative demand for reliability of short-term earthquake predictions.

Acknowledgment

The authors take pleasure in thanking Dr. S. Shimada from National Research Institute for Earth Science and Disaster Prevention and Prof. N.Yonekura from University of Tokyo for helpful discussions.

References

(1)Ida, Y.(1991): Interpretation of seismic and volcanic activities in the Izu Block in relation to collision Tectonics, *J. Phys. Earth*, 39, 421-440.

(2)Kato, T., M. Imae, M. Sasaki, M. Murata, H. Kunimori (1995) : Application of space techniques to geodesy and geodynamics in Japan, *J. Phys. Earth*, 43, 629-655.

(3)Kimata, K. (1996) : Horizontal displacement at Kozu-Jima detected by GPS Measurements (Dec. 1990- Oct. 1995) (In Japanese).

(4)Lastochkin, A. N. (1978) : Structural geo-

morphological investigations on the shelfs, *Leningrad, Nedra*.
(5)Murata, M. (1993) : Observing geodynamics from the analysis of 7.3-Year LAGEOS data, *Geodynamics Series* Vol. 23, *Contributions of Space Geodesy to Geodynamics* ; *Crustal Dynamics*.
(6)Polonska (Monakhova), D. (1991): Morphometric analysis of the block structure of Bulgarian litrtoral and shelf. *Ph. D. thesis, Moscow State Univ., Geographical faculty*, (in Russian).
(7)Seno,T., S. Stein and A. E. Gripp (1993) : A model for the motion of the Philippine Sea Plate consistent with NUVEL-1 and geological data, *Journal of Geophysical Research*, Vol.98, No B10, pp. 17, 941-17, 948.
(8)Simonov, Yu. G. (1972) : Geomorphologic analysis for the regions, *Moscow State Univ*. (in Russian).
(9)Shimada, S. (1994) : Recent crustal movement observed by the NIED Kanto-Tokai GPS fixed-point network-methodology and results, R*eprint from the proceedings of the 9th Joint Meeting of the UJNR Panel on Earthquake Prediction Technology*.
(10)Shimada, S. and Y. Bock (1992) : Crustal deformation measurements in Central Japan determined by a Global Positioning System fixed-point network, *Journal of Geophysical Research*, Vol. 97, No. B9.
(11)Somerville, P. (1978) : The accomodation of plate collision by deformation of the Izu block, Japan, *Bull. Earthquake Res. Inst. Univ. Tokyo*, 53, 629-648.
(12)Tsuji, H., Y.Hatanaka and S. Miyazaki (1996): Tremors Monitoring crustal deformations in Japan, *GPS* World.
(13)Ukawa, M. (1991) : Collision and fan-shaped compressional stress pattern in the Izu block at the northern edge of the Philippine Sea Plate, *Journal of Geophysical Research*, Vol. 96, No. B1, pp. 713-728.

Appendix

Applied in present investigation morphotectonic analysis is the latest stage of sequentially evolved subdisciplines of structural geomorphology. Principal ideas of the structural geomorphology were proposed by I.P.Gerasimov in 1949. Later the concept was developed by other scientists in the USSR as well as abroad ; Yu. A. Mescheryakov, Ya. D. Zekkel, K.I. Gerenchuk, J. Tricard, P. Birau, K. K. Markov, K. Olier, A.V. Orlova, G. I. Khudyakov, Yu. G. Simonov and others.

Further this methodology have been branched in relation to the main units of the Earth surface. The structural geomorphology of the plain *Mescheryakov*, [1965] and mountains [*N. P. Kostenko*, 1972 ; *Yu. G. Simonov*, 1972 ; *A. V. Orlova*, 1975 ; *G. I. Khudyakov*, 1977 and others] has been developed first. Another branch is the structural geomorphology of the sea shores and sea floor. Most essential in the structural investigations of the coasts is that here the exogenic processes possess especially high energy. The sea abrasion, which proceeds more intensively than erosion of most rivers, in many cases results in the leveling of blocks with different dynamics. The leveling of more stable blocks occurs here sufficiently fast and the block pattern could be traced only in the straight lines of the coast. It is accepted that on the seashores the structural characteristics in the relief may occur only in the cases of high neotectonic activity or of their long inherited development. Very important in this field are the investigations of A. K. Lastochkin [1986], L. G. Nikiforov [1984], E. G. Mayev [1988], V. I. Myslivets [1989], D.I. Polonska (Monakhova) [1991].

In this work we followed applied by Prof.