Tectonophysics, 144 (1987) 151-158
Elsevier Science Publishers B.V., Amsterdam - Printed in The Netherlands

Interpretation and Analysis of Observations

The relative movement of the North American and Pacific plates in 1984-1985, detected by the Pacific VLBI network

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(Received December 2, 1985; revised version accepted April 5, 1986)

Abstract

Heki, K., Takahashi, Y., Kondo, T., Kawaguchi, N., Takahashi, F. and Kawano, N., 1987. The relative movement of the North American and Pacific plates in 1984-1985, detected by the Pacific VLBI network. In: R.L. Wesson, Mechanics of Earthquake Faulting. *Tectonophysics*, 144: 151-158.

Very long basline interferometry (VLBI) experiments from stations on the North American and Pacific plates in the period 1984-1985 revealed that the interplate baselines have undergone changes by several centimeters which are consistent with the values expected from the model of present plate kinematics. It was also clarified that the intraplate baseline lengths are almost stationary in this period. These results demonstrate that the relative movement of these two plates in the last two years is similar to the plate motion observed on a geological time scale, say a few millions of years.

Introduction

Information on the velocity of the relative movement of tectonic plates has been provided mainly by ocean magnetic anomaly data (Minster and Jordan, 1978). However, such data do not have time resolution shorter than the periods of the geomagnetic field reversals, say from a few tens of thousands of years to a few millions of years. Hence it will be of much geophysical importance to measure such motions with higher temporal resolution. Recent development of technology such as satellite laser ranging (SLR) and very long baseline interferometry (VLBI) has enabled us to monitor such relative plate motion in a time scale of one or two years (Coates et al., 1985).

VLBI is a type of interferometer that observes distant celestial radio sources using widely separated multiple antennas equipped with independent and accurate atomic clocks. Its basic function is to measure the difference of the arrival time of the radio wave from a star with a precision of a few tenths of nanoseconds. VLBI was originally developed as a precise radio telescope by radio astronomers to detect the positions or the structures of the radio sources with high angular resolution. On the other hand, such delays also contain geodetic information such as earth orientation parameters (EOP) and the vectors connecting the antennas (which we call the baseline vector). Thus, the potential of VLBI as a new, precise geodetic tool is being watched with keen interest by earth scientists.

The precise values of the EOP have been routinely determined by the American and European International Radio Interferometric

0040-1951/87/$03.50

Surveying (IRIS) VLBI network (Carter et al., 1985) beginning several years ago. The experiment to detect large scale crustal movements from the secular variation of the positions of the stations began as the Crustal Dynamics Project (CDP) by the National Aeronautics and Space Administration (NASA), U.S.A. (Coates et al., 1985). In Japan, the Kashima Space Research Center, Radio Research Laboratory (RRL), began to participate in this project in 1984 with a 26 m ∅ parabolic antenna and a K-3 VLBI system, which was developed at Kashima (Kondo et al., 1985; Kuroiwa et al., 1985) and is completely compatible with the Mark III VLBI system used worldwide (Rogers et al., 1983). Here we present the outline of the experiments and their station configurations and the observed baseline length evolution in the period 1984–1985.

VLBI experiment

Experimental procedures

Figure 1 shows the basic components of the VLBI system. One experiment usually consists of a few hundred observations of various radio stars, typically quasars, visible from the stations. The observations are almost automatically executed over 1 or 2 days according to the schedule distributed to every station in advance. Two frequency bands (2 GHz and 8 GHz) are used in the observation in order to remove the ionospheric effect. Received radio signals are converted down to video frequencies and are digitally recorded on magnetic tapes. After the experiments, these tapes are transported to a cross-correlation station (in our case, either Haystack Observatory, U.S.A., or the Kashima Space Research Center, Japan). Then these tapes are cross-correlated and time delays and the time derivatives of the delays (delay rates) are obtained for each pair of the stations. Detailed descriptions of the experiments and the data reduction are available in Clark et al. (1985).

Participating stations

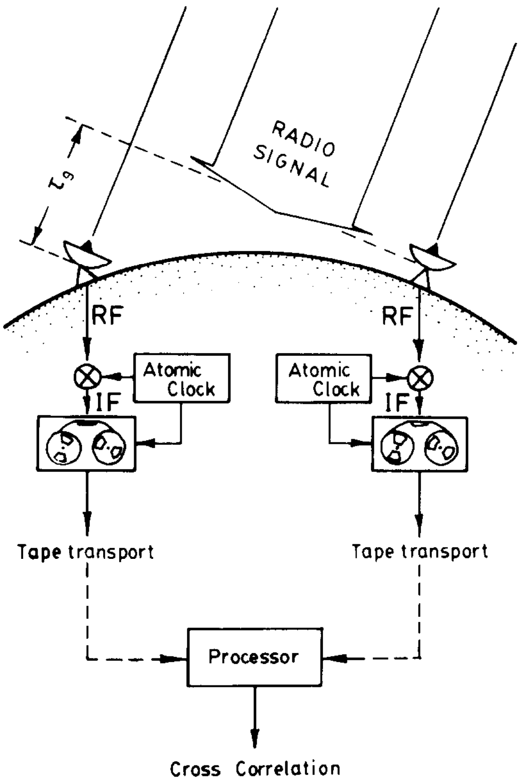

Fig. 1. A schematic diagram of very long baseline interferometry (VLBI). Radio emissions from celestial radio sources are received simultaneously by two or more radio telescopes. These signals are recorded on magnetic tapes with the signals from the atomic clocks such as hydrogen masers. These tapes are transported to a cross-correlation station and are processed to obtain accurate delay times (τ_g).

From 1984 to 1985, Kashima station joined in the experiments listed in Table 1. The positions of the stations in Table 1 is illustrated in Fig. 2. The experiments, with the intention of detecting the relative motion between the North American and Pacific plates, began as the Western Pacific (WPAC) experiment in 1984. In 1985, two other experiments, the Eastern Pacific (EPAC) and the Northern Pacific (NPAC) experiments were started for the same purpose. In Fig. 2, the VLBI stations participating in the WPAC experiment in 1984 are connected with each other. They are the Kashima (Japan), Kauai (Hawaii), Kwajalein (Marshall Islands), Gilcreek (near Fairbanks, Alaska) and Mojave (California) stations.

In Fig. 3, the plate boundaries are drawn using a Mercator projection with the pole at the relative rotation pole (Euler pole) of the Pacific and North American plates (Minster and Jordan, 1978).

TABLE 1

Participating stations in the Japan–US joint VLBI experiments in 1984–1985.

Experiment name		Period	Participating stations
SLE-1	1984	Jan. 03–04	KAS–MOJ
SLE-2		Feb. 24–25	KAS–MOJ–HAT
WPAC-1 [a]		Jul. 28–30	KAS–MOJ–KWA–KAU–GIL
WPAC-2 [a]		Aug. 04–06	KAS–MOJ–KWA–KAU–GIL
POLAR-1		Aug. 30–31	KAS–MOJ–HAY–WET–GIL–ONS
POLAR-2		Sep. 02–03	KAS–MOJ–HAY–WET–GIL–ONS
NPAC-1	1985	May 15–16	KAS–MOJ–HAT–KAU–VAN–GIL
POLAR-1		Jun. 19–21	KAS–MOJ–WST–WET–GIL–ONS
EPAC-1		Jul. 06–08	KAS–MOJ–KWA–KAU–GIL–VAN
WPAC-1		Jul. 20–22	KAS–MOJ–KWA–KAU–GIL–VAN
EPAC-2		Jul. 27–29	KAS–MOJ–KWA–KAU–GIL–VAN
WPAC-2		Aug. 10–12	KAS–MOJ–KWA–KAU–GIL–VAN
NPAC-2		Sep. 30–Oct. 01	KAS–MOJ–HAT–KAU–VAN–GIL
POLAR-2 [b]		Nov. 21–23	KAS–MOJ–WST–WET–GIL–ONS

SLE—System level experiment; WPAC—Western Pacific experiment; NPAC—Northern Pacific experiment; EPAC—Eastern Pacific experiment; KAS—Kashima; KWA—Kwajalein; HAY—Haystack; MOJ—Mojave; KAU—Kauai; WET—Wettzell; HAT—Hatcreek; GIL—Gilcreek; ONS—Onsala; VAN—Vandenberg; WST—Westford.

[a] Divided into two parts in data analyses.

[b] Data not included in this paper.

Therefore, in this figure, when viewed from the North American plate, the movement of the Pacific plate is represented as the linear leftward motion as indicated by the large arrow. Among these stations, Kauai and Kwajalein belong to the Pacific plate. The Gilcreek and Mojave stations are located on the North American plate. Kashima is located on the east coast of Honshu Island, which used to be considered as belonging to the Eurasian plate (Chapman and Solomon, 1976). However, recent studies (Kobayashi, 1983; Nakamura, 1983) suggest that the North American–Eurasian plate boundary lies between northern Honshu and the Japan Sea and that northern Honshu, including Kashima, is a part of the North American plate (Fig. 4). Seno (1985) hypothesized that northern

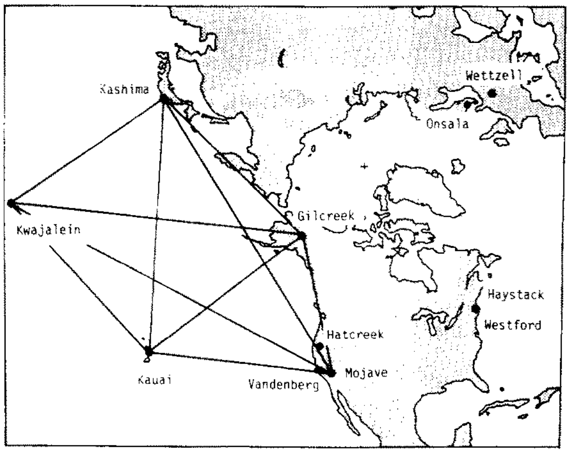

Fig. 2. Station positions listed in Table 1. The stations participating in the WPAC-1 experiment in 1984 are connected with each other. + denotes the north pole.

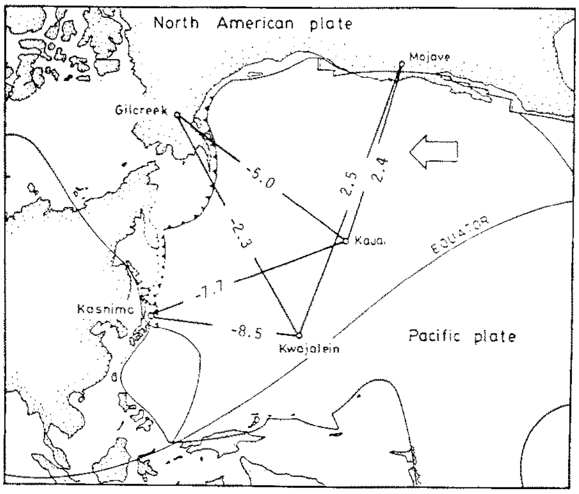

Fig. 3. The stations which took part in the WPAC-1 experiment in 1984 are shown with the plate boundaries, using a Mercator projection with the pole at the relative rotation pole of the Pacific plate and North American plate. The direction of the movement of the Pacific plate is represented as the linear leftward motion when viewed from the North American plate (large arrow). The expected changing rates of the interplate baseline lengths are indicated for each baseline (unit = cm/yr.). Positive and negative values represent lengthening and shortening respectively.

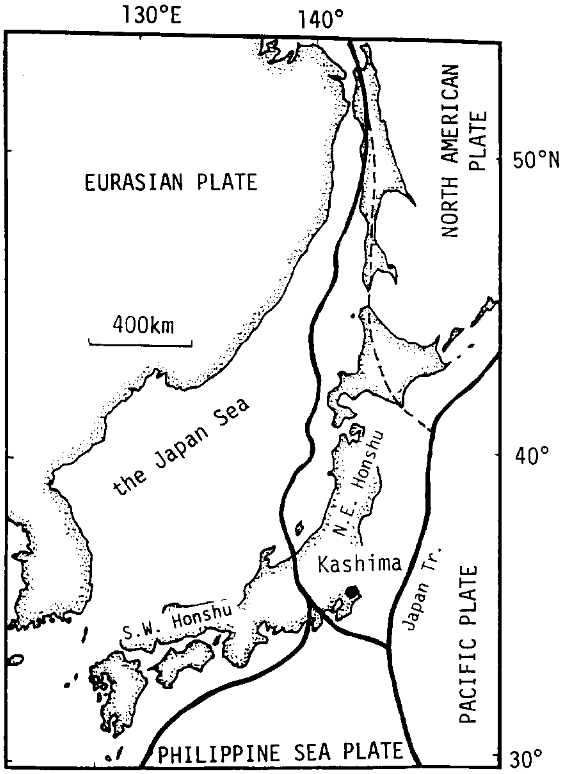

Fig. 4. Plate boundaries around Japan (solid lines), redrawn after Seno (1985). The broken line shows the North American–Pacific plate boundary by Chapman and Solomon (1976).

Honshu might be a microplate behaving sometimes as a part of the Eurasian plate and at other times as a part of the North American plate.

Data analysis

In VLBI data analyses, several parameters are selected according to the purpose of the experiment and are adjusted by the least-squares method using the residuals of the observed delays from the expected delays. Usually, such parameter adjustments are done independently by many researchers using the same observed delay and delay rate data. In our case, the data analyses were done both at our laboratory and at the NASA Goddard Space Flight Center (GSFC). In our analyses, station positions, except that of the reference station (in the WPAC experiments, the Mojave station), atmospheric zenith path lengths for all stations, and the coefficients of the clock polynomials are selected as the parameters to be adjusted. IRIS data (Carter et al., 1985) are used for the a-priori EOP values. The IRIS data give the EOP of every 5 days without smoothing correction. In our case, firstly short period tidal terms (less than 35 days) obtained by Yoder et al. (1981) were subtracted from IRIS data, and the results were then interpolated. Then, short period tidal terms subtracted in advance were added to this interpolated value. We adopted the radio source positions in the last catalog of the GSFC (Ryan and Ma, 1985).

The atmospheric excess paths were calculated from the Marini model (Marini, 1972) and meteorological data. The excess paths in magneto-ionic media (the ionosphere and solar corona) were corrected by combining the data of two frequencies (2 GHz and 8 GHz). The cable delays were also corrected by using cable delay counters. The analyses at the GSFC are almost similar to our methods except that the EOP values are from the Bureau International de l'Heure (BIH) Circular D values. However, the differences in the EOP values only affect the directions of the baselines and do not affect the baseline lengths to be discussed in this study.

After the adjustments of the parameters, the residuals of the observed delays and delay rates from the expected values reach about 0.1 ns and 0.1 ps, respectively. This implies that the baseline components are determined with the formal errors of about 3 cm. Both the uncertainties of the delay and delay rate observables due to thermal noises and the systematic errors due to unmodeled physical effects (e.g., fine structures of the radio sources and inadequacy of the tropospheric delay model) are considered to be responsible for these final errors.

Results of the parameter adjustments are usually somewhat different among the researchers who analyzed the data, reflecting the personal judgements in selecting the clock parameters to be adjusted, bad data to be discarded, and so on. We checked the consistency of our results with those obtained independently by GSFC researchers (C. Ma, pers. commun., 1985) and confirmed that these two results do not have serious discrepancies.

Baseline length results

Baseline length rates of change expected from plate tectonics

The expected rates of change are derived by assuming the position of the instantaneous relative rotation pole (Euler pole) and the rotation rate for these plates. Figure 3 shows the rates of change of the lengths of the interplate baselines in the WPAC experiment calculated according to the standard plate kinematic model, RM-2 by Minster and Jordan (1978). The positive and negative values represent the lengthening and shortening respectively. These baseline length changes are not uniform even for the same pair of the plates. For example, the baselines connecting the Pacific stations and the Californian station change by only 2–3 cm in a year while the baselines connecting the Kashima and Pacific stations change by 7–9 cm in a year. Generally speaking, the baseline length change is larger when the baseline direction is closer to the direction of the relative plate motion and is the largest when the two stations are 90° apart from their Euler pole. Needless to say, the baseline lengths for the stations on the same plate are expected to be stationary.

Observed baseline length change in the period 1984–1985

Figures 5 and 6 show examples of the baseline length evolution in 1984–1985. Not only the WPAC experiment, but also the baseline length results obtained in the 1984 and 1985 experiments (except 1985 Polar-2) (Table 1) are included in the figures. 1984 WPAC-1 and WPAC-2 are divided into the first and second halves because their data bases are divided into two parts. The error bars attached to the individual data are the 1-sigma formal errors obtained in the least-squares analyses of the data.

Figure 5 shows examples of 2 of the intraplate baselines. It is expected that no significant changes occur for such baselines if the plates are really rigid. This figure also shows the best-fit lines (solid lines) for observed baseline length changes. Our results demonstrate that there are no significant trends for these baselines, supporting our original assumption that these stations are located on the same rigid plate.

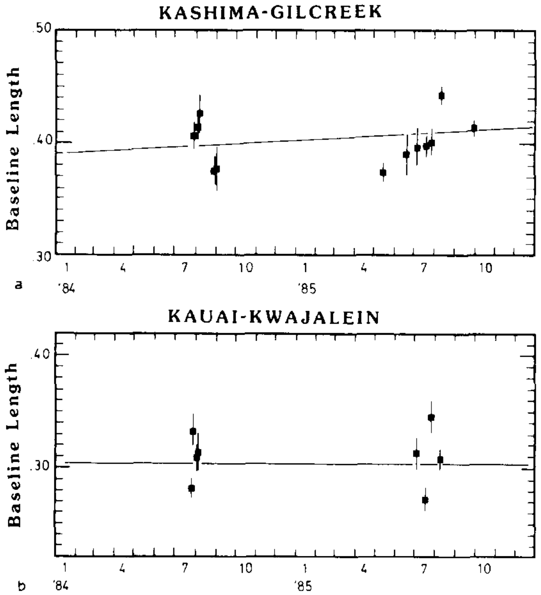

Fig. 5. Baseline length evolution for intraplate baselines. a. Kashima–Gilcreek. b. Kauai–Kwajalein. The ordinates represent a baseline length minus 5,427,104 m in (a), and a baseline length minus 3,725,196 m in (b). The abscissa represents the experiment time (year and month). One sigma error bars are shown for the baseline lengths. Solid lines indicate the best-fit lines for the observed baseline lengths. In this case, the expected baseline length changes are zero.

Figure 6 shows the results for 2 of the interplate baselines. In these figures, rates of change of baseline length calculated from the RM-2 model are also illustrated as broken lines, as well as the observed changing rates. The observed slopes are very close to those expected, which suggests that the relative motion between the Pacific and North American plates during the period 1984–1985 is very similar to the motion modeled as the average over a geological time scale.

Causes of the dispersion of the baseline length results

In Fig. 6, although the best-fit lines are not inconsistent with the plate tectonic model, the differences between several baseline data and the best-fit lines are much larger than the formal

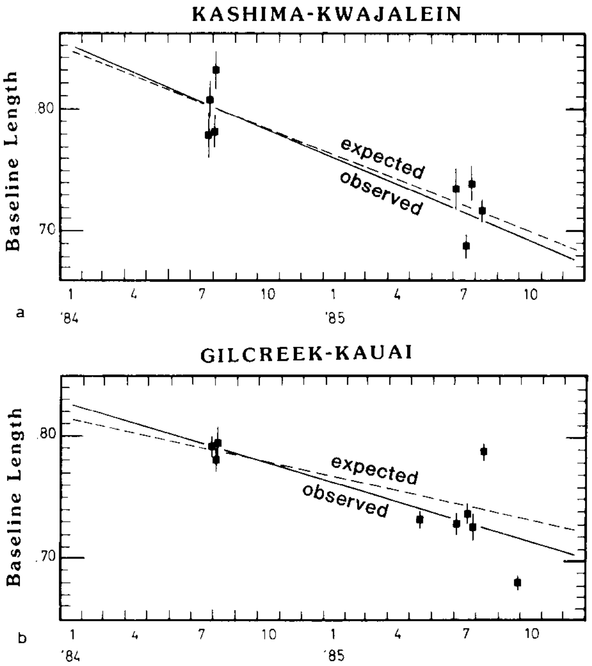

Fig. 6. Baseline length evolution for interplate baselines. a. Kashima–Kwajalein. b. Gilcreek–Kauai. The ordinates represent a baseline length minus 3,936,330 m in (a), and a baseline length minus 4,728,114 m in (b). The abscissa and the error bars are the same as those in Fig. 5. Solid lines indicate the best-fit lines for the observed baseline lengths. Broken lines show the changes of the baseline lengths expected from the plate kinematic model (Minster and Jordan, 1978).

errors of their lengths. We can suggest two reasons. One reason is that the actual behavior of the baseline lengths is so complicated that their evolution can not be modeled by simple linear regression. Another reason is that there still remain several unmodelled physical effects which affect the baseline length results. We consider the latter to be more plausible because baseline lengths are sometimes greatly scattered even for experiments separated only by a few days. It is one of the most important future problems to make our physical models more complete.

In order to clarify the actual nature of the baseline evolution, it is also meaningful to increase the frequency of the VLBI experiments. NASA and RRL intend to do monthly trans-Pacific VLBI experiments from the spring of 1986. We will be able to obtain more continuous baseline evolution data using the results derived from this monthly experiment program.

Plate tectonic implication of the results

In Fig. 7 we compared the baseline length changes observed in the period 1984–1985 and those expected from the RM-2 model. The ordinate and the abscissa denote the expected and observed values respectively. One sigma error bars are at-

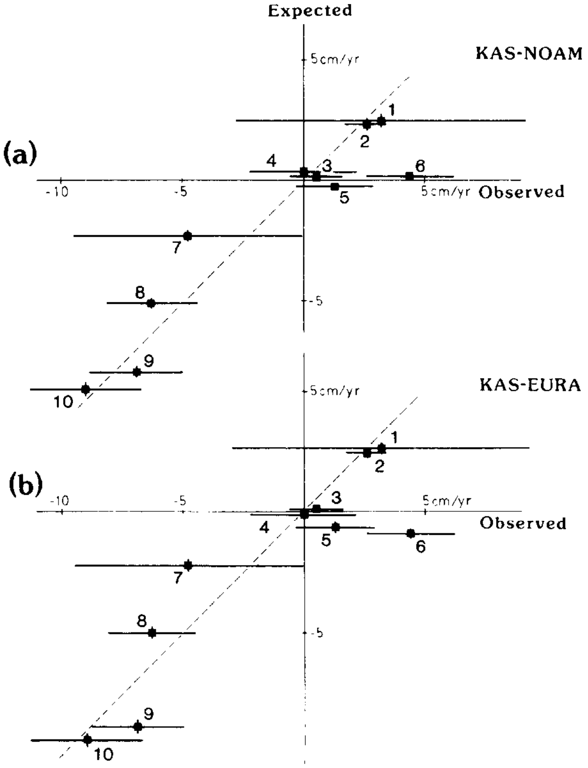

Fig. 7. Comparison of the expected and the observed baseline length change. a. Kashima, belonging to the North American plate. b. Kashima belonging to the Eurasian plate. The ordinate represents the baseline length change expected from the plate motion model RM-2 (Minster and Jordan, 1978). The errors for the expected values are calculated from the formal errors in the RM-2 model (see text). The abscissa represents the baseline length changes obtained by the linear regression for the baseline length evolution data in the period 1984–1985. Error bars for the observed values are 1-sigma formal errors of the slopes of the best-fit lines, scaled using the residuals after the linear regression. If the observed and expected changes are concordant, these data should lie on the broken lines which have a slope of 45°. Numbers in the figure indicate the data for the following baselines: *1* = Mojave–Kwajalein; *2* = Mojave–Kauai; *3* = Mojave–Gilcreek; *4* = Kauai–Kwajalein; *5* = Kashima–Gilcreek; *6* = Kashima–Mojave; *7* = Kwajalein–Gilcreek; *8* = Kauai–Gilcreek; *9* = Kashima–Kauai; *10* = Kashima–Kwajalein.

tached to both of the values. The errors of the observed slopes are the 1-sigma formal errors scaled using the residuals after the linear regressions. The errors for the expected values are calculated from the formal errors of the relative rotation pole position and the rotation speed in RM-2. In Fig. 7a, expected values are calculated assuming that the Kashima station belongs to the North American plate as suggested by recent works. The intraplate baselines are characterized by zero expected values. If the expected and observed values are concordant, the data are considered to lie on the broken line with a gradient of 45°. Although there are several discordant data, most of the data seem to be in good agreement, considering their errors.

In Fig. 7b, the Kashima station is assumed to belong to the Eurasian plate and the expected values for the 4 baselines involving the Kashima station are therefore somewhat different from Fig. 7a. It is shown that the data are also in good agreement with this model and it seems impossible, at present, to distinguish which model better represents the results. However, we expect that these two models will become distinguishable after data for longer time spans are accumulated.

One of the serious problems in this kind of study is the local scale deformation. Unfortunately, currently operational fixed VLBI stations are not ideally distributed, that is, several of them are so close to the plate boundaries such as San Andreas Fault system or the Japan Trench that there might be some contamination of the plate motion by local deformation. It is therefore important to monitor such deformation by local scale VLBI experiments or other techniques such as conventional ground geodetic surveys. We are now developing a small transportable VLBI system which can be used to monitor such local deformation. The Global Positioning System (GPS) will also be a powerful tool for monitoring the intraplate deformation (e.g., Dixon et al., 1985). It is also important to establish larger VLBI networks and to test the global consistency of the baseline length changes under the assumption of the rigid plate movements. Such studies will determine tectonic plate rigidity on a time scale of a few years, compared to the assumed rigidity on a geological time scale.

Acknowledgements

We thank our colleagues at the Kashima Space Research Center: Taizo Yoshino, Yuji Sugimoto, Hiroshi Kuroiwa, Shin-ichi Hama, Hiroo Kunimori, Jun Amagai, Noriyuki Kurihara, Hitoshi Kiuchi, Akihiro Kaneko, Munetoshi Tokumaru, Kunimasa Koike and Tadashi Shiomi for their help and encouragement. We are also grateful to many foreign VLBI researchers in NASA and other organizations for their collaboration and for providing unpublished data.

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