# Excess Westward Velocities of Minamitorishima (Marcus) and Kwajalein VLBI Stations from the Expected Velocities Based on Rigid Motion of the Pacific Plate

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(Received July 17, 1995; Revised February 15, 1996; Accepted February 16, 1996)

# 南鳥島 (Marcus) および Kwajalein 超長基線電波干渉計観測局の太平洋プレートに対する西向きの局速度について

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(1995 年 7 月 17 日 受付, 1996 年 2 月 15 日 改訂, 1996 年 2 月 16 日 受理)

## 要　　旨

地質学的に求められたプレート運動モデルに束縛されない局速度を求めるため，南鳥島 (Marcus) および Kwajalein 局の参加した超長基線電波干渉計 (VLBI) 実験のデータの再解析を行った．個々の実験で推定された GLB932 座標系における局位置に対して最小 2 乗推定によって局速度を求め，

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NUVEL-1A モデルで北米プレートに対する太平洋プレートの運動から期待される速度と比較した結果，いずれも有為な速度の差が認められた．この速度の差の一部は太平洋プレートの北米プレートに対する運動のオイラー極ベクトルの推定値を用いることによって小さくすることができるが，それでも南鳥島局で 6 mm/year，Kwajalein 局で 10 mm/year の西向きの速度残差が残される．両局の局速度に GLB932 解で与えられた Kauai 局の局速度を加えて太平洋プレートの北米プレートに対するオイラー極ベクトルを求めた結果，オイラー極の位置は NUVEL-1A とよい一致を示したが，回転角速度は NUVEL-1A の値よりも有意に大きい ( $\sim 8.9\%$ ) という結果が得られた．これらの結果は，太平洋プレートの北米プレートに対する速度が NUVEL-1A モデルよりも大きいこと，太平洋プレートの一部に非剛体的な運動がある可能性を示している．

**Abstract.**

All the geodetic Very Long Baseline Interferometry sessions in which either the Minamitorishima (Marcus) or the Kwajalein station was involved were reanalyzed to get velocities of these stations without a constraint from a geologically determined plate motion model. Velocities of these two stations were obtained by the least squares estimation on a series of session-by-session site coordinates in the GLB932 reference frame. Comparison of the estimated site velocity with an expected site velocity from the NUVEL-1A plate motion model showed significant difference at each station. Part of these discrepancies can be reduced if an estimated Euler vector of the Pacific Plate motion with respect to the North American Plate is used. However, excess westward velocities of 6 mm/year for Minamitorishima and 10 mm/year for Kwajalein

remain. The position of the Euler pole estimated from Minamitorishima, Kwajalein, and Kauai site velocities show a good agreement with the NUVEL-1A Euler pole, whereas the estimated angular velocity is significantly ($\sim 8.9\%$) faster than that of the NUVEL-1A model. These results suggest that the Pacific Plate is moving faster than the NUVEL-1A model with respect to the North American Plate, and that the rigidity of the Pacific Plate does not hold in a region around the Minamitorishima and Kwajalein VLBI stations.

## 1. Introduction

Minamitorishima and Kwajalein are Very Long Baseline Interferometry (VLBI) observation sites located in the western region of the Pacific Plate. Site velocities of these two stations obtained by the VLBI observations along with those of the Kauai station are very useful for studying the behavior of the tectonic motion of the Pacific Plate. Minamitorishima (also known as Marcus Island) VLBI station was established by the Communications Research Laboratory (CRL) in 1989 as a part of the Western Pacific VLBI Network Project (Kunimori *et al.*, 1993). From 1989 through 1993, 16 geodetic VLBI sessions were coordinated by CRL in cooperation with the National Aeronautics and Space Administration (NASA) and Shanghai Observatory of the Chinese Academy of Sciences. Kwajalein VLBI station was established as a part of the Crustal Dynamics Project (CDP) in 1984 by NASA. From 1984 through 1989, 20 geodetic VLBI sessions were performed (Bosworth *et al.*, 1993).

Geodetic VLBI data obtained from the experiments performed worldwide since 1979 have been repeatedly analyzed by the Space Geodesy Program team at the Goddard Space Flight Center (GSFC) of NASA and the results have been published annually in the annual report of the program (Ma *et al.*, 1994). The latest solution, designated GLB932, which was submitted to the International Earth Rotation Service (IERS), includes results from all the experiments carried out before the end of 1993 and this was chosen for study here. This solution gives the coordinates of radio sources in a celestial reference frame, a series of Earth Orientation Parameters (position of the Earth's rotation pole, nutation offsets from IAU 80 nutation model (Seidelmann, 1982), and UT1−UTC), and a set of site coordinates of VLBI stations in a terrestrial reference frame. Among the 119 stations included in the solution, 35 stations were constrained to move consistently with the NNR-NUVEL1 plate motion model (Argus and Gordon, 1991), 39 stations were constrained to have zero vertical velocities, and 16 stations of the remaining 45 stations located close to other stations were constrained to

move at the same velocity as the adjacent stations. Therefore, the site velocities of the remaining 29 core stations were estimated only from the geodetic VLBI data without being constrained except that the origin and the rotation of the terrestrial reference frame were constrained with the NNR-NUVEL1 plate motion model. Excluding sites located close to plate boundaries from these 29 stations, 10 stations are located on the North American Plate and one station (Kauai) is located on the Pacific Plate. Minamitorishima and Kwajalein stations are not included in these core stations because uncertainties of velocities of these two stations were larger than 3 mm/year in an unconstrained solution before the GLB932 solution was created. Their vertical velocities were constrained to be zero in the solution. To obtain site velocities of these two stations relying only on the geodetic VLBI data without an effect of such a constraint, all the geodetic VLBI sessions in which either the Minamitorishima or the Kwajalein station participated were reanalyzed. On the other hand, site velocities at Kauai, Kwajalein and Minamitorishima stations expected from the NUVEL-1A (DeMets *et al.*, 1995) plate motion model were calculated and compared with the VLBI site velocities. To derive site velocities from the NUVEL-1A model, first the Euler vector of the North American Plate with respect to the GLB932 terrestrial reference frame was estimated from GLB932 site velocities of stations on the North American Plate. The Euler vector of the Pacific Plate / North American Plate pair from the NUVEL-1A model was then subtracted from the Euler vector of the North American Plate to get the Euler vector of the Pacific Plate with respect to the GLB932 terrestrial reference frame.

## 2. Data Analysis

Data were analyzed using the geodetic VLBI analysis software package CALC (Version 8.1) and SOLVE (Version 5.0039) developed by the Space Geodesy Program team at GSFC (Ma *et al.*, 1994). Coordinates of all the radio sources observed in the experiments were given by the GLB932 solution. Daily series of UT1−UTC and

Earth's rotation pole position of Earth Orientation Parameters (EOP) were given by the EOP90C04 daily series (IERS, 1994) but offsets and their time derivatives between EOP90C04 and GLB932 solutions were estimated by the least squares method and added to the EOP90C04 series to maintain consistency with the GLB932 solution. This was done because the EOP series of GLB932 does not provide daily series of the EOP but only the EOP values at the time each geodetic VLBI experiment was performed. These *a priori* parameters were fixed and were not adjusted through the least square estimation process. The site coordinate of Kashima (26 m or 34 m), Fairbanks (AK, USA), Seshan (China), and Canberra (Australia) stations were also fixed at the value obtained from the GLB932 solution. The MTT (Mapping Temperature Test) mapping function was used for tropospheric delay correction (Herring, 1992).

To find the best interval of parameter epoch for clock offsets and hydrostatic atmospheric zenith delay, three different intervals (60 minutes, 120 minutes, and 180 minutes) were examined. The offsets of nutation from the conventional IAU 80 nutation model given in the EOP90C04 were also examined against the estimated offsets from the VLBI data. Table 1 compares the weighted RMS of residuals of site positions from the linearly fitted motion and the reduced chi-square of the fit. The comparison suggests that the estimated nutation offsets are favored to the EOP90C04 values and the best time interval of parameter epoch is 120 minutes for Minamitorishima experiments and 180 minutes for Kwajalein experiments. This seems reasonable since the frequency standard at Minamitorishima station was a hybrid system of a highly stable crystal oscillator and a Cesium frequency standard, except for the sessions in 1993. The crystal-Cesium hybrid system is less stable compared with a hydrogen maser frequency standard system.

Tables 2 and 3 give the site positions expressed in the local coordinate system estimated for Minamitorishima station at 16 individual VLBI sessions and for Kwajalein VLBI station at 20 individual VLBI sessions, respectively. Uncertainties given in the

tables are one standard deviation. Parameters of error ellipses in the horizontal plane are also given in the tables.

A site coordinate at any time epoch and a site velocity can be estimated by the least square criterion from a series of site coordinates given in Tables 2 and 3. By using the procedure described by Koyama *et al.* (1994), site velocities and site coordinates at the epoch 1988.0 were estimated for Minamitorishima and Kwajalein stations. The estimated site velocities are presented in Table 4. The chi-square ($\chi^2$) of the least square fit was calculated to be 68.5 and 213.0 for Minamitorishima and Kwajalein, respectively, from which the reduced chi-square ($\bar{\chi^2}$) become 1.63 and 3.94 by dividing $\chi^2$ by the degrees of freedom, which are 42 and 54 in this case. These values are both larger than 1 and are outside the 95% central distribution of the reduced chi-square. This suggests either that the uncertainties evaluated in Tables 2 and 3 are underestimated or that there is anomalous site motion which is not consistent with a linear motion model. If the linear motion model is assumed, the square root of these reduced chi-square should be multiplied to formal standard deviations to obtain uncertainties statistically consistent with the distribution of the residuals. Errors of site velocities in Table 4 are products of one standard deviation and the square-root of the reduced chi-square. Figures 1 and 2 show the estimated site positions from individual VLBI observing sessions projected onto the local horizontal planes with error ellipses of 95% confidence limit. Estimated linear site motions are also indicated in the figures by broad shaded lines and filled circles on the line which indicate the site positions at various epochs. Residuals of site positions from the estimated linear site motion tend to be larger in the earlier VLBI sessions. The repeatability of the site coordinates determined from the geodetic VLBI experiments are greatly affected by the systematic error caused by inaccurate *a priori* information like the Earth Orientation Parameters. The number of geodetic VLBI sessions in use has been increasing year by year; therefore, the EOP series in the EOP90C04 solution is less accurate in the early years and is improving

year by year. This may explain why the reduced chi-squared value was larger for the Kwajalein station than for the Minamitorishima station. Figure 3 shows the estimated site velocities at these two stations and GLB932 site velocity at Kauai station projected on the Earth's surface.

## 3. Site velocities expected from the NUVEL-1A model

To obtain the site velocities expected from the NUVEL-1A model, the plate motion of the North American Plate on the GLB932 terrestrial reference frame has to be evaluated. First, the North American Plate's motion with respect to the GLB932 reference frame was investigated from the GLB932 site velocities of 10 VLBI stations. Generally, the motion of a tectonic plate can be represented by an Euler vector. For an Euler vector $\mathbf{\Omega}$, the plate motion velocity $\mathbf{v}_i$ at point $\mathbf{r}_i$ is given by

$$\mathbf{v}_i = \mathbf{\Omega} \times \mathbf{r}_i, \tag{1}$$

The intersection of the Euler vector and the surface of the Earth is called an Euler pole. The plate moves around the axis defind by the Euler pole and the center of the Earth at an angular velocity $\omega$ defined by the length of the Euler vector. The above equation can be rewritten as the following relation:

$$\mathbf{v}_i = \mathrm{P}_i \mathbf{\Omega} \tag{2a}$$

$$\mathrm{P}_i = \begin{pmatrix} 0 & r_{zi} & -r_{yi} \\ -r_{zi} & 0 & r_{xi} \\ r_{yi} & -r_{xi} & 0 \end{pmatrix} \tag{2b}$$

where $\mathbf{r}_i = (r_{xi}\ r_{yi}\ r_{zi})^{\mathrm{T}}$. Since the above equation is a linear expression of $\mathbf{r}_i$ by $\mathbf{\Omega}$ and $|\mathrm{P}_i| \neq 0$, the vector $\mathbf{\Omega}$ can be estimated by the linear least square estimation method from site velocities at two or more different points on the plate. The least square estimate $\hat{\mathbf{\Omega}}$ of $\mathbf{\Omega}$ from $m$ site velocities is given by

$$\hat{\mathbf{\Omega}} = (\mathrm{P}^{\mathrm{T}}\mathrm{W}_2\mathrm{P})^{-1}\mathrm{P}^{\mathrm{T}}\mathrm{W}_2\mathrm{V}, \tag{3a}$$

where

$$\mathrm{P} = \begin{pmatrix} \mathrm{P}_1 \\ \mathrm{P}_2 \\ \vdots \\ \mathrm{P}_m \end{pmatrix}, \qquad \mathrm{V} = \begin{pmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \vdots \\ \mathbf{v}_m \end{pmatrix}. \tag{3b}$$

$\mathrm{W}_2$ is the weighting matrix defined by the inverse of the error matrix of V.

First, ten stations, i.e. Algonquin, Fairbanks, Fort Davis, Green Bank, Los Alamos, Maryland Point, Pie Town, Richmond, Westford, and Yellowknife, were used to estimate the Euler vector. Figure 4 shows the GLB932 site velocities of these stations projected on the surface of the Earth. As the result, the site velocities at Fort Davis, Los Alamos, Pie Town, and Yellowknife have large residuals outside the 95% confidence level uncertainty ellipses of GLB932 site velocities. GLB932 site velocity of the Yellowknife station has large uncertainty and the velocity residuals from the estimated plate motion are comparable to the 95% confidence limit of error. The other three stations are located near the deforming zone between the Pacific Plate and the North American Plate; therefore, it is likely that these sites are moving with respect to the North American Plate. The reduced chi-square of the least square estimate was as large as 41.8 by using all the 10 stations. If these four stations are excluded from the estimation of $\mathbf{\Omega}$, the reduced chi-square decreases to 8.6. Therefore, the four stations were excluded from the estimation of the Euler vector. The estimated location of the Euler pole is shown in the Figure 4 with its 95% confidence error ellipse. Figure 5 compare the site velocities expected from the estimated Euler vector and the GLB932 horizontal site velocities. As expected, the comparison shows a good agreement between two velocities at all six stations.

The Euler vector of the Pacific Plate's motion with respect to the GLB932 reference frame based on the NUVEL-1A model, $\mathbf{\Omega}_{\mathrm{pa}}^{\mathrm{NUVEL-1A}}$, is obtained from the NUVEL-1A Euler vector of the Pacific Plate with respect to the North American Plate, $\mathbf{\Omega}_{\mathrm{pa-na}}^{\mathrm{NUVEL-1A}}$,

and the estimated Euler vector of the North American Plate with respect to the GLB932 reference frame $\mathbf{\Omega}_{\rm na}^{\rm VLBI}$ by

$$\mathbf{\Omega}_{\rm pa}^{\rm NUVEL-1A} = \mathbf{\Omega}_{\rm pa-na}^{\rm NUVEL-1A} - \mathbf{\Omega}_{\rm na}^{\rm VLBI}. \tag{4}$$

Next, the Euler vector of the Pacific Plate's motion with respect to the GLB932 reference frame based on the VLBI data, $\mathbf{\Omega}_{\rm pa}^{\rm VLBI}$, was also estimated from the three site velocities at Minamitorishima, Kwajalein and Kauai shown in Figure 3. The reduced chi-square of the least square estimate was 3.8. Figure 6 compares the VLBI site velocities at these three stations with those expected from the $\mathbf{\Omega}_{\rm pa}^{\rm NUVEL-1A}$ and $\mathbf{\Omega}_{\rm pa}^{\rm VLBI}$ in the horizontal plane. This comparison shows significant difference between VLBI site velocities and the site velocities expected from the NUVEL-1A model at all of the three stations. According to the results, these stations are moving westward in addition to the Pacific Plate's motion predicted by the NUVEL-1A model. By using the estimated Euler vector $\mathbf{\Omega}_{\rm na}^{\rm VLBI}$, the difference becomes smaller. But there still are significant difference at Kwajalein ($\sim$ 10mm) and marginally significant difference at Minamitorishima ($\sim$ 6mm).

The Euler vector of $\mathbf{\Omega}_{\rm pa-na}^{\rm NUVEL-1A}$ is also compared with the VLBI based Euler vector $\mathbf{\Omega}_{\rm pa-na}^{\rm VLBI}$, which is defined by $\mathbf{\Omega}_{\rm pa}^{\rm VLBI} - \mathbf{\Omega}_{\rm na}^{\rm VLBI}$, in Figure 7. Although the locations of the Euler poles show quite good agreement, the angular velocity from the VLBI based Euler vector is significantly faster than that of NUVEL-1A model at 95% level of confidence.

## 4. Discussion

Gordon and Stein (1992) discussed active deformation zones along tectonic plate boundaries, where plates are deforming as a result of interactions between individually moving plates. Along a subducting plate boundary between an oceanic plate and a continental plate, the active deformation zone is usually hundreds of kilometers wide but most of it is within the overriding continental plate. Since both Minamitorishima

and Kwajalein are located far enough from the plate boundary between the Pacific Plate and other plates, it seems reasonable to regard these sites as situated in a stable region of the Pacific Plate. However, the results shown in Figure 6 suggest that the rigid-plate hypothesis is not adequate at Minamitorishima and Kwajalein. If the NUVEL-1A Euler vector of the Pacific / North American Plate pair is assumed correct, all the three sites on the Pacific Plate are moving westward at 6 - 17 mm/year in addition to the rigid tectonic motion. Even if the NUVEL-1A model is not assumed and the Euler vector estimated from VLBI data is used, Minamitorishima and Kwajalein stations have excess westward velocity at 6 mm/year and 10 mm/year respectively.

Rigidity of tectonic plates were investigated by Argus and Gordon (1994) but the rigidity was confirmed only for the continental plates since there were not enough VLBI stations in oceanic plates. It is, therefore, possible that an oceanic plate may behave non-rigidly. The NUVEL-1A plate motion model between the Pacific Plate and the North American Plate is constructed mainly from spreading rates along the mid ocean ridge in the Pacific ocean and directions of transverse strike slip faults in western North America. Thus, it does not use any data from the subducting plate boundary at the western edge of the Pacific Plate. Both the NUVEL-1A model and the site velocities obtained by VLBI are satisfied if the Pacific Plate is not rigid but the western part of the plate is moving faster than the eastern part of the plate. Alternatively, the excess westward velocities of these three stations can be explained by a difference in time scale. The VLBI-determined site velocities represent velocities averaged over 5 to 10 years, but the geological plate motion models represent velocities averaged over the last few million years. Heki *et al.* (1993) discussed that site motions near a plate boundary can be characterized by episodic motions rather than smooth motions seen in the inner stable region of tectonic plates from their measurements by using Global Positioning System receivers near a divergence boundary of tectonic plates. The episodic motions near the plate boundary propagate into the inner part of the plates by the law of diffusion. If the

attenuation of the diffusion is small, site velocities at Minamitorishima and Kwajalein stations measured over a comparably short time scale such as 4 years may differ from site velocities averaged over the last few million years.

The other point of discussion is the angular velocity of the Pacific Plate with respect to the North American Plate. The angular velocity of NUVEL-1A is a revision of the NUVEL-1 model (DeMets *et al.*, 1990) according to the recent revision of the geomagnetic reversal time scale. The angular velocity of NUVEL-1A is slower by about 4.38% than the NUVEL-1 model. As already described in this paper, the angular velocity of the Pacific Plate with respect to the North American Plate was estimated to be $0.816 \pm 0.029$ (degrees per million years) from the VLBI-based site velocities. The estimated angular velocity is about 9.0% faster than the NUVEL-1A model and 4.2% faster than the NUVEL-1 model. Apparently, the recent revision of the geomagnetic reversal time scale increased the gap between the VLBI-based angular velocity and the geological plate motion model as far as the pair of Pacific Plate and the North American Plate is concerned. The same tendency can be seen in the studies by Heki (1995), Sato (1993), and Argus and Gordon (1994). Heki (1995) investigated the factor needed to be multiplied to the angular velocities between various pairs of plates in the NUVEL-1 model to fit the VLBI site velocity data. The factor was estimated to be $1.013 \pm 0.023$, where the error is one sigma formal error. This result is not consistent with the recent revision of the geomagnetic reversal time scale incorporated into the NUVEL-1A plate motion model. Sato (1993) used baseline length rates of VLBI data and estimated the angular velocity as $0.827 \pm 0.035$ (degrees per million years) which is consistent with the result obtained in this paper. Argus and Gordon (1995) estimated the angular velocity as $0.79 \pm 0.03$ (degrees per million years) by using the four years of Global Positioning System (GPS) data. They discussed a possibility of speed up of plate motion in the last 3 million years.

## 5. Conclusions

Site coordinates of the Minamitorishima and Kwajalein VLBI station were estimated by analyzing 16 and 20 VLBI observing sessions, respectively. Site velocities of both the stations were estimated using the least square method. Chi-square analyses suggest that the uncertainties of the site coordinates obtained for each session are underestimated especially for the Kwajalein experiments. Therefore, the uncertainties of the site velocities are adjusted by multiplying square roots of the reduced chi-square values. These site velocities and the site velocity of the Kauai VLBI station given by the GLB932 solution were compared with the site velocities expected from the NUVEL-1A plate motion model at these stations. If the Pacific Plate's motion given by the NUVEL-1A model with respect to the North American Plate is assumed to be correct, current motions of these three VLBI stations measured by means of geodetic VLBI have excess westward velocities with respect to the Pacific Plate. The discrepancies are 6 and 17 mm/year which are statistically significant at 95% confidence level as shown in Figure 6, l. These velocity discrepancies can be reduced by adopting the estimated Euler vector from the VLBI site velocities, but discrepancies of 6 mm/year for Minamitorishima and of 10 mm/year for Kwajalein still remain. From these results, it is concluded that there are excess westward velocities with respect to the Pacific Plate at least at Minamitorishima and at Kwajalein. According to this conclusion, the rigidity of the Pacific Plate does not hold at least for the time interval of a few to ten years, over which the VLBI measurements have been performed. It is, however, not conclusive whether the excess velocities are variable or invariable with time. To answer the last question, it is necessary to extend the time span of available geodetic VLBI data or to combine VLBI data with other space geodetic data, i.e. Global Positioning System and Satellite Laser Ranging.

## Acknowledgments

The author would like to thank colleagues at the Communications Research Laboratory and the Shanghai Observatory of the Chinese Academy of Sciences for Western Pacific VLBI Network experiments. Observations at Minamitorishima VLBI station were greatly supported by the Defense Agency and the Meteorological Agency of Japan. Two of the 16 VLBI sessions at the Minamitorishima station and all of the 20 VLBI sessions at the Kwajalein station were supported by the Dynamics of Solid Earth program of the National Aeronautics and Space Administration (NASA). Software developed at Goddard Space Flight Center of NASA and data provided by the International Earth Rotation Service were extensively used in our study. Discussions with Dr. Donald Argus of Jet Propulsion Laboratory and Dr. Kosuke Heki of the National Astronomical Observatory, and suggestions from two anonymous reviewers were quite helpful to complete this paper.

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**Figure 1.** Estimated site positions of the Minamitorishima VLBI station projected onto the local horizontal plane. Each ellipse shows the one standard deviation estimated by analyzing an individual geodetic VLBI session. The shaded broad line is the line of best fitted site motion with filled circles which represent site positions at 1989.5, 1990.5, 1991.5, 1992.5, and 1993.5.

**Figure 2.** Estimated site positions of the Kwajalein VLBI station projected onto the local horizontal plane. Each ellipse shows the one standard deviation region estimated by analyzing an individual geodetic VLBI session. The shaded broad line is the line of best fitted site motion with filled circles which represent site positions at 1985.5, 1986.5, 1987.5, 1988.5, and 1989.5.

**Figure 3.** Horizontal site velocities of 10 VLBI stations on the North American Plate based on the GLB932 solution. Ellipses at the ends of the velocity vectors show uncertainties at the 95% confidence limit. The location of the Euler pole estimated from six stations is also shown by a filled square with 95% confidence limit error ellipse.

**Figure 4.** Horizontal site velocities of three VLBI stations on the Pacific Plate. Site velocity of Kauai station is from the GLB932 solution, whereas site velocities of Minamitorishima and Kwajalein stations are the estimated velocities given in Table 4. Ellipses at the ends of the velocity vectors show uncertainties at 95% confidence limit.

**Figure 5.** Horizontal site velocities of six VLBI stations on the North American Plate. The solid arrows represent the horizontal site velocities from the GLB932 solution. The shaded arrows represent the expected horizontal site velocities calculated from the estimated Euler vector. The Euler vector is estimated from site velocities of the six VLBI stations. Error ellipses at the ends of solid arrows give uncertainties of the site velocities at 95% confidence level, scaled by the square root of the reduced chi-square.

**Figure 6.** Horizontal site velocities of three VLBI stations on the Pacific Plate with respect to the GLB932 reference frame. Solid arrows show the site velocity from the GLB932 solution for Kauai station and estimated site velocities for Minamitorishima and the Kwajalein stations. Shaded arrows show site velocities calculated from the estimated Euler vector of the Pacific Plate with respect to the GLB932 reference frame. Broken arrows show the site velocities expected from NUVEL1A plate motion model based on the North American Plate's motion. Error ellipses on the ends of solid arrows give uncertainties of the site velocities at 95% confidence level, scaled by the square root of the reduced chi-square.

**Figure 7.** Location of the Euler pole and angular velocity (inset) of the Pacific Plate's motion with respect to the North American Plate. Filled squares are for the VLBI estimate and filled circles are for the NUVEL-1A model. Error ellipses of the Euler pole location and error bars of the angular velocity are evaluated by 95% confidence limit. Square root of the reduced chi-square was used to scale the estimation error of the Euler pole location and the angular velocity estimated from VLBI data.

**Table 1.** Comparison of results with different analysis conditions.

| | Minamitorishima Experiments | | | | Kwajalein Experiments | | | |
|---|---|---|---|---|---|---|---|---|
| nutation offsets : | estimated | | fixed | | estimated | | fixed | |
| Epoch Interval | WRMS | $\bar{\chi^2}$ | WRMS | $\bar{\chi^2}$ | WRMS | $\bar{\chi^2}$ | WRMS | $\bar{\chi^2}$ |
| 60 min. | 12.5mm | 1.63 | 12.3mm | 1.59 | 11.60mm | 3.77 | 12.0mm | 4.14 |
| 120 min. | 12.2mm | 1.63 | 12.4mm | 1.69 | 11.37mm | 3.87 | 11.9mm | 4.39 |
| 180 min. | 14.6mm | 2.43 | 14.6mm | 2.46 | 11.20mm | 3.94 | 11.6mm | 4.35 |

Weighted RMS of residuals and reduced chi-square were calculated based on a least-square estimate of a linear site motion model. Three different interval of clock and atmospheric delay epochs were examined together with the combination whether nutation offsets were estimated or fixed with the IERS EOP90C04 values.

**Table 2.** Site displacements of Minamitorishima VLBI station.

| Session Date | Site Displacements (mm) | | | Error Ellipse ($1\sigma$) | | |
|---|---|---|---|---|---|---|
| | *Eastward* | *Northward* | *Upward* | $\sigma_{\max}$ | $\sigma_{\min}$ | $\zeta$ |
| 1989 Jul.24 | $-98.3 \pm 22.3$ | $7.1 \pm 24.1$ | $-153.7 \pm 95.9$ | 27.6 | 17.8 | $-39.4°$ |
| 1989 Aug.12 | $-77.1 \pm 22.8$ | $44.1 \pm 23.0$ | $-157.0 \pm 96.9$ | 27.7 | 16.8 | $-44.7°$ |
| 1990 Jun.25 | $-188.1 \pm 8.2$ | $54.9 \pm 10.2$ | $25.7 \pm 37.3$ | 10.2 | 8.2 | $9.0°$ |
| 1990 Jun.30 | $-170.5 \pm 10.7$ | $48.4 \pm 11.5$ | $88.9 \pm 40.9$ | 12.9 | 9.0 | $-38.7°$ |
| 1991 Jun.27 | $-227.3 \pm 14.0$ | $49.7 \pm 14.4$ | $-66.8 \pm 50.6$ | 17.7 | 9.5 | $-43.5°$ |
| 1991 Jun.28 | $-254.1 \pm 16.7$ | $65.4 \pm 16.8$ | $-39.0 \pm 60.7$ | 20.7 | 11.6 | $-44.6°$ |
| 1991 Jun.30 | $-236.1 \pm 12.8$ | $70.2 \pm 13.4$ | $24.8 \pm 54.7$ | 14.3 | 11.9 | $-36.4°$ |
| 1991 Jul. 1 | $-223.8 \pm 15.5$ | $45.9 \pm 16.3$ | $12.7 \pm 54.1$ | 19.8 | 10.5 | $-42.6°$ |
| 1991 Jul. 2 | $-241.3 \pm 14.4$ | $53.6 \pm 15.3$ | $-47.9 \pm 50.1$ | 18.6 | 9.7 | $-42.2°$ |
| 1991 Jul. 3 | $-245.9 \pm 13.5$ | $76.6 \pm 14.3$ | $9.7 \pm 47.8$ | 17.3 | 9.3 | $-41.8°$ |
| 1991 Jul. 4 | $-251.5 \pm 15.2$ | $55.8 \pm 15.5$ | $48.2 \pm 64.8$ | 16.7 | 13.9 | $-41.1°$ |
| 1992 Jun.25 | $-337.5 \pm 13.3$ | $98.2 \pm 14.0$ | $-46.2 \pm 56.7$ | 15.3 | 11.8 | $-39.5°$ |
| 1992 Jun.28 | $-339.2 \pm 12.0$ | $97.9 \pm 12.3$ | $172.0 \pm 49.7$ | 13.6 | 10.4 | $-41.7°$ |
| 1993 Jun.24 | $-393.6 \pm 8.7$ | $120.9 \pm 8.6$ | $37.2 \pm 34.0$ | 9.6 | 7.5 | $-46.4°$ |
| 1993 Jun.26 | $-390.8 \pm 7.8$ | $118.7 \pm 7.7$ | $12.1 \pm 35.6$ | 8.5 | 6.9 | $-46.2°$ |
| 1993 Jun.28 | $-419.4 \pm 4.1$ | $121.3 \pm 4.4$ | $-39.0 \pm 20.4$ | 4.6 | 3.9 | $33.5°$ |

Site displacements of Minamitorishima VLBI station are calculated in the local coordinate system with the origin at (X: $-5227446855.0mm$, Y: $2551379198.0mm$, Z: $2607604852.0mm$) which is the GLB932 solution at the epoch 1988.0. Errors are expressed by one standard deviations. $\sigma_{\max}$ and $\sigma_{\min}$ are the angular lengths of one sigma error ellipse in the horizontal plane, and $\zeta$ is the azimuth of the major axis of the error ellipse measured clockwise from north.

**Table 3.** Site displacements of Kwajalein VLBI station.

| Session Date | Site Displacements (mm) | | | Error Ellipse ($1\sigma$) | | |
|---|---|---|---|---|---|---|
| | *Eastward* | *Northward* | *Upward* | $\sigma_{\max}$ | $\sigma_{\min}$ | $\zeta$ |
| 1984 Jul. 7 | $273.3 \pm 9.2$ | $-126.1 \pm 17.0$ | $-48.0 \pm 35.5$ | 18.5 | 5.5 | 24.6° |
| 1984 Jul.21 | $298.2 \pm 17.4$ | $-127.8 \pm 28.7$ | $-71.4 \pm 61.4$ | 31.6 | 11.5 | 26.5° |
| 1984 Jul.22 | $328.6 \pm 11.8$ | $-91.5 \pm 19.1$ | $95.1 \pm 42.2$ | 21.0 | 8.2 | 26.4° |
| 1984 Jul.28 | $249.7 \pm 6.0$ | $-54.3 \pm 14.1$ | $-40.8 \pm 37.4$ | 14.1 | 6.0 | 2.0° |
| 1984 Jul.29 | $261.6 \pm 6.8$ | $-112.8 \pm 16.0$ | $18.3 \pm 37.8$ | 16.2 | 6.3 | 9.8° |
| 1984 Aug. 4 | $270.1 \pm 5.6$ | $-111.7 \pm 12.3$ | $-87.7 \pm 33.6$ | 12.3 | 5.4 | 7.1° |
| 1984 Aug. 5 | $279.2 \pm 6.7$ | $-96.2 \pm 15.8$ | $28.2 \pm 40.3$ | 15.8 | 6.6 | 4.6° |
| 1985 Jul. 6 | $193.5 \pm 9.6$ | $-62.7 \pm 16.6$ | $9.9 \pm 36.5$ | 17.5 | 7.7 | 21.2° |
| 1985 Jul.20 | $202.2 \pm 3.6$ | $-52.7 \pm 8.2$ | $51.5 \pm 23.7$ | 8.3 | 3.4 | 7.9° |
| 1985 Jul.27 | $195.1 \pm 8.4$ | $-64.3 \pm 12.8$ | $50.9 \pm 33.3$ | 13.9 | 6.3 | 26.3° |
| 1985 Aug.10 | $183.0 \pm 3.6$ | $-55.8 \pm 8.4$ | $21.7 \pm 22.0$ | 8.4 | 3.5 | 6.4° |
| 1986 Jul. 5 | $143.7 \pm 9.6$ | $-20.9 \pm 13.5$ | $5.1 \pm 38.1$ | 15.4 | 6.1 | 31.6° |
| 1986 Jul.12 | $123.4 \pm 4.8$ | $-51.0 \pm 9.8$ | $-28.7 \pm 28.8$ | 10.0 | 4.5 | 10.6° |
| 1986 Jul.26 | $143.0 \pm 10.3$ | $-25.9 \pm 14.1$ | $17.2 \pm 44.4$ | 16.1 | 6.8 | 32.3° |
| 1986 Aug. 2 | $129.6 \pm 3.4$ | $-44.8 \pm 7.7$ | $17.5 \pm 21.6$ | 7.7 | 3.2 | 9.9° |
| 1988 Jul.16 | $-54.3 \pm 4.3$ | $18.5 \pm 5.9$ | $37.5 \pm 24.5$ | 5.9 | 4.2 | −0.6° |
| 1988 Jul.24 | $-68.0 \pm 6.2$ | $6.5 \pm 8.4$ | $11.0 \pm 28.9$ | 9.1 | 5.0 | 28.3° |
| 1988 Jul.30 | $-52.6 \pm 5.1$ | $16.4 \pm 6.7$ | $-37.9 \pm 27.9$ | 6.7 | 5.1 | −0.6° |
| 1988 Jul.31 | $-64.4 \pm 7.0$ | $22.4 \pm 9.1$ | $163.1 \pm 55.8$ | 9.1 | 7.0 | −6.6° |
| 1988 Aug. 6 | $-39.4 \pm 4.3$ | $6.1 \pm 6.1$ | $-14.7 \pm 27.4$ | 6.2 | 4.2 | 13.2° |

Site displacements of Kwajalein VLBI station are calculated in the local coordinate system with the origin at (X: $-6143536474.0mm$, Y: $1363997197.0mm$, Z: $1034707474.0mm$) which is the GLB932 solution at the epoch 1988.0. Errors are expressed by one standard deviations. $\sigma_{\max}$ and $\sigma_{\min}$ are the angular lengths of one sigma error ellipse in the horizontal plane, and $\zeta$ is the azimuth of the major axis of the error ellipse measured clockwise from north.

**Table 4.** Site velocities in the local coordinate systems.

| Station | Site Velocities (mm) | | | Error Ellipse ($1\sigma$) | | |
|---|---|---|---|---|---|---|
| | *Eastward* | *Northward* | *Upward* | $\sigma_{\max}$ | $\sigma_{\min}$ | $\zeta$ |
| Minamitorishima | $-78.9 \pm 2.5$ | $24.4 \pm 2.7$ | $-6.2 \pm 10.9$ | 2.8 | 2.4 | $-31.4°$ |
| Kwajalein | $-81.5 \pm 1.6$ | $27.9 \pm 2.7$ | $3.6 \pm 8.9$ | 2.7 | 1.5 | $11.4°$ |

Errors are expressed by one standard deviations multiplied with the square root of the reduced chi-square. $\sigma_{\max}$ and $\sigma_{\min}$ are the angular lengths of one sigma error ellipse in the horizontal plane multiplied with the square root of the reduced chi-square, and $\zeta$ is the azimuth of the major axis of the error ellipse measured clockwise from north.

**Table 5.** Plate motion parameters of Pacific Plate with respect to the North American Plate.

| | Longitude | Latitude | $\omega$ | $\sigma_{\max}$ | $\sigma_{\min}$ | $\zeta$ |
|---|---|---|---|---|---|---|
| VLBI | 79.1°W | 49.8°N | $0.816 \pm 0.029$ | 2.2° | 0.1° | 49.8° |
| NUVEL-1A | 78.2°W | 48.7°N | $0.749 \pm 0.012$ | 1.3° | 1.2° | −61° |

Angular velocity $\omega$ is in degrees per million years measured clockwise. Errors are expressed by one standard deviations. $\sigma_{\max}$ and $\sigma_{\min}$ are the angular lengths of one sigma error ellipse, and $\zeta$ is the azimuth of the major axis of the error ellipse measured clockwise from north.