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An Estimate of the Philippine Sea Plate Motion Derived from the Global Positioning System Observation at Okino Torishima, Japan

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沖ノ鳥島における GPS 観測によって得られたフィリピン海プレートの運動について

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要　　旨

沖ノ鳥島はフィリピン海プレートの中央部にあってフィリピン海プレートの運動の監視には極めて重要な点である．この島の護岸に設置された一等三角点において1989年以来 GPS 観測が繰り返し実施された．これらのうち1992年6月，1994年6月，1995年3月，同年5月，及び1996年4月の観測データを解析した．本土側で観測された点のうち，つくば (GS15) を基準点として基線解析を行い，沖ノ鳥島の観測点の変位速度を算出した．解析に際しては ITRF93 基準座標系を用い，国際 GPS サービス機構 (IGS) から精密暦を入手して基線解析を行った．得られた結果から直線近似で沖ノ鳥島の変位速度ベクトルを求めたところ，$(Vns, Vew)=(1.08\pm0.81, -2.77\pm1.04)$cm/yr となった．これに，Heki (1996) によって求められているつくばのユーラシアプレート安定地塊に対する変位速度を考慮したところ $(Vns, Vew)=(3.00\pm0.84, -5.17\pm1.06)$cm/yr となった．これは Seno *et al.* (1993) によって地震のスリップベクトルから求められているユーラシアに対するフィリピン海プレートの Euler ベクトルから算出された $(Vns, Vew)=(2.87, -5.81)$cm/yr に極めて近い．このことから，沖ノ鳥島が最近少なくとも数百年間は定常的に運動していると考えてよいと思われる．

Abstract

Okino Torishima (Parece Vela) is an isolated island located in the midst of the Philippine Sea plate. Different from other islands in the plate, the island is not contaminated by either local volcanic activity or non-rigid deformation near plate boundary. Thus, monitoring of its displacement may represent rigid motion of the plate. A series of GPS observations at this island with other peripheral sites have been conducted since 1989. We have analysed recent data of 1992, 1944, 1995 and 1996, since precise orbits are available only for these observations. Tsukuba was assumed to be moving according to ITRF93 velocity field. Displacement of Okino Torishima by this assumption suggests that the island is moving toward WNW with a rate of $Vns=1.08(\pm0.81)$cm/yr and $Vew=-2.77(\pm1.04)$cm/yr or $2.97(\pm1.07)$cm/yr toward N68.7(±16.1)°W. Taking recent estimate of local velocity of Tsukuba relative to the stable Eurasian plate by Heki (1996) into account, the velocity of Okino Torishima relative to Eurasian craton is estimated to be $Vns=3.00(\pm0.84)$cm/yr and $Vew=-5.17(\pm1.06)$cm/yr. This result is well consistent with the velocity estimated from seismic slip vectors by Seno *et al.* (1993) ($Vns=2.87$ cm/yr, $Vew=-5.81$ cm/yr). The present result seems to suggest that the Philippine Sea plate is moving steadily at least in the recent hundreds of years.

1. Introduction

The Philippine Sea plate (PH) is a purely oceanic plate and has neither diverging nor transform plate boundary. Thus its relative motion with respect to the surrounding plates has been estimated using only indirect evidence such as slip vectors of large earthquakes that have occurred at converging plate interface. Because slip vectors are not necessarily precise indicators of relative rigid motions, motion of PH relative to the surrounding plates has not been estimated precisely (e.g. Ranken *et al.*, 1984; Seno *et al.*, 1993). Recent developments of the space techniques such as Very Long Baseline Interferometry (VLBI) or the Global Positioning System (GPS) have provided us with more direct and accurate tools in determining relative plate motions.

The difficulty in determining the Philippine Sea plate motion using space techniques is that the plate is purely oceanic and only a small number of isolated islands are sparcely distributed in it. Moreover, most of these islands such as Northern Mariana

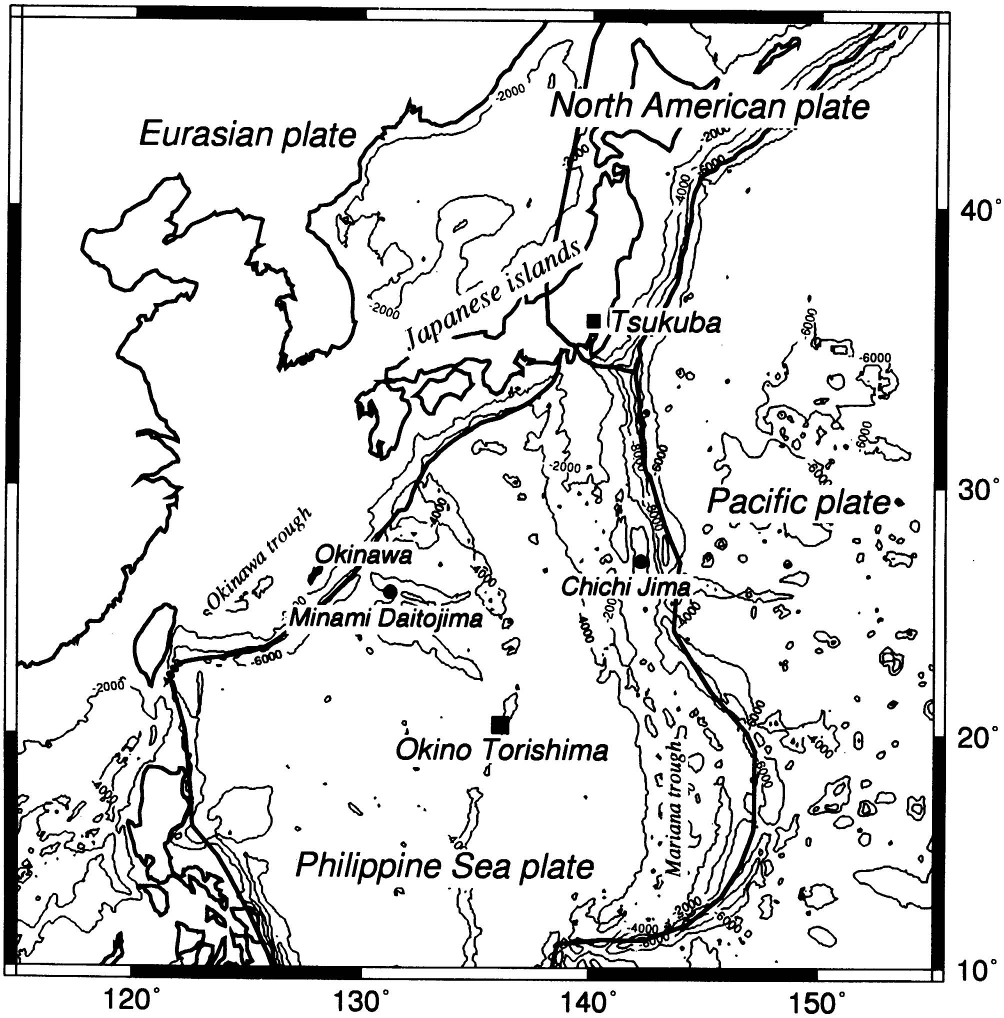

Fig. 1. The Philippine Sea plate and the western Pacific area.

islands, and Izu-Bonin islands are located close to the plate boundary, so that displacements of these islands might be contaminated by the non-rigid deformations close to the plate boundary. Also many of such islands seem to suffer from other local deformations such as local volcanic activity or back arc spreading and may not represent rigid component of displacements of the plate. Yet a number of observations revealed that the motions at these islands are reasonably consistent with rigid plate motion models (e.g., Matsuzaka *et al.*, 1991; Kimata *et al.*, 1994; Disaster Prevention Research Institute, 1994; Yu and Chen, 1994).

Okino Torishima (Parece Vela) is a small coral reef with the size of 4 km(EW) × 2 km(NS) and is located nearly in the central part of the plate (Figure 1), in which a small number of cays are exposed above the sea surface. Since the island is located at

Table 1. History of GPS observation at Okino Torishima.

	Date	Institutes	Receiver used
(1)	November 1989	GSI	MiniMac 2816
(2)*	June, 1992	GSI, ERI	Trimble 4000SST
(3)	February, 1994	GSI, ERI, JAMSTEC	Ashtech P-12
(4)*	June, 1994	HD, GSI, ERI	Trimble 4000SSE
(5)*	March, 1995	GSI, ERI, JAMSTEC	Ashtech Z-XII3
(6)*	May, 1995	HD, GSI, ERI	Trimble 4000SSE
(7)	February, 1996	GSI, ERI, JAMSTEC	Trimble 4000SSE
(8)*	April, 1996	HD, GSI, ERI	Trimble 4000SSE

*: Data used in this study
(1): Precise orbits were not available
(3): L2 phase was not recorded
Participating Institutes:
GSI: Geographical Survey Institute
ERI: Earthquake Research Institute, University of Tokyo
HD: Hydrographic Department, Maritime Sefety Agency
JAMSTEC: Japan Marine Science and Technology Center

least 700 km from the nearest plate boundary, it is not affected by non-rigid deformation at plate boundary, nor by any local volcanic deformations. Thus, monitoring its displacement will provide us with an estimate of the Euler vector of the Philippine Sea plate relative to the surrounding plates, which, in turn, enables us to evaluate the effect of non-rigid motion near plate boundaries and/or local deformations at other peripheral sites.

Cays of Okino Torishima are only small patches of coral blocks with the size of about 2 to 3 meters in diameter. Although there is an control point established by the Hydrographic Department previously, the GPS observations were possible only at the geodetic control points that were established by the Geographical Survey Institute on the sea walls constructed to protect the cays. There are two control points; one is the first order control point at the east sea wall and the other is the third order control point at the north sea wall. We used the first order control point as the fundamental observation site (site name: OKEU), together with other sites for collocations.

GPS observations at the island has been made since 1989 by various institutes (Table 1). Since 1992, those institutes cooperatively conducted a series of GPS observation at the island to monitor its displacements. In this article, we show results of baseline analysis for Tsukuba-Okino Torishima baseline for the five times of recent observations and the estimated displacements are compared with otherwise estimated relative plate motion models.

2. Data and Analysis

Observations at the island have been done since 1989 (Table 1). Because the precise orbits of GPS satellites, which is essential for the accurate baseline estimates, were not available before 1991 and the P-codeless receiver was used in 1989, 1989 data were not used in this study. Also, in 1994 campaign, we failed to track L2 phase because Anti-Spoofing, which encrypt P-code to Y-code for military use, was implemented just before the campaign and we were not able to handle the receiver properly against this implementation. Since it is essential for long baseline analysis to use both L1 and L2 for correction of ionospheric effects, we were not able to use 1994 data for accurate base-line estimates either. Observation sessions of February 1996 campaign were only a few hours, so that we gave up using these data.

Consequently, we used only data taken in June 1992, February 1994, March 1995, May 1995, and April 1996 in this study. In each campaign, more than two days of observations were conducted. Each session used 30 seconds of sampling interval. In the earlier campaigns, the GPS observations were limited only in the day time for the safety of the field surveyers. Thus only several hours of sessions were possible in 1992. In later campaigns, at least one 24 hour session was conducted at a campaign by leaving the receiver at the site unattended during the night time.

For data analysis, we employed Bernese ver. 3.5 baseline analysis software (Rothacher *et al.*, 1993a). Just since June 1992, International GPS Service for Geodynamics (IGS) began to disseminate precise orbits and Earth rotation parameters (ERP) produced from the global tracking network through INTERNET. The IGS CODE orbits and its ERP were employed in the analysis through this facility (Rothacher *et al.*, 1993b).

Since Tsukuba site (site name: GSI5) has been occupied together with Okino Torishima, Tsukuba was used as the reference site where ITRF (IERS Terrestrial Reference Frame) coordinates and its velocity based on NNR-NUVEL-1 (Argus and Gordon, 1991) was assumed, which we refer to as ITRF93 (Boucher *et al.*, 1994). The corresponding site coordinates of Okino Torishima (OKEU) were estimated for each session, together with tropospheric zenith delay parameters for every 3 hours interval. After the baseline analysis for each session, average coordinates and their variance-covariance matrices for each campaign were estimated. Linear regression analyses were conducted from the obtained five times of results using weighted least squares method to estimate the velocity of the island.

3. Results

Figure 2 shows thus obtained time series of horizontal coordinates of Okino Torishima. Large uncertainty in 1992 results seems to stem from short occupation duration in the campaign. However, it may be readily seen that Okino Torishima shows linear drift toward north with $Vns=1.08(\pm 0.81)$cm/yr and west with $Vew=-2.77(\pm 1.04)$cm/yr, where positive signs are taken toward north and east, respectively. In the present study, vertical displacements were not discussed because vertical components were highly noisy and no significant deformation was found in the data.

Figure 3 is the plots of the horizontal positions of the Okino Torishima site with its

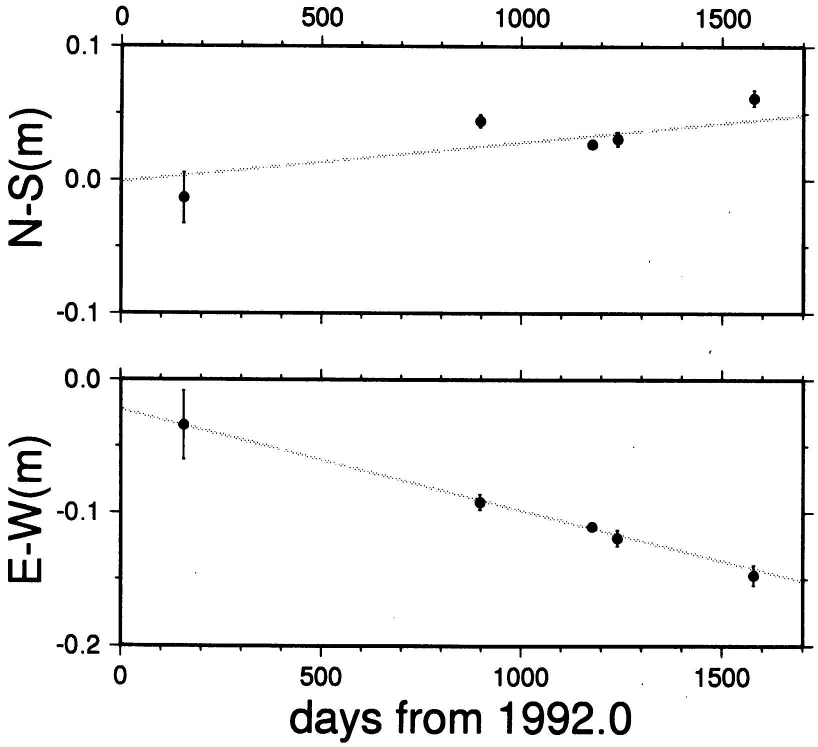

Fig. 2. Time series of horizontal coordinates of Okino Torishima assuming ITRF93 velocity at Tsukuba. NS direction (upper) and EW direction (lower). Error bars are 1 σ.

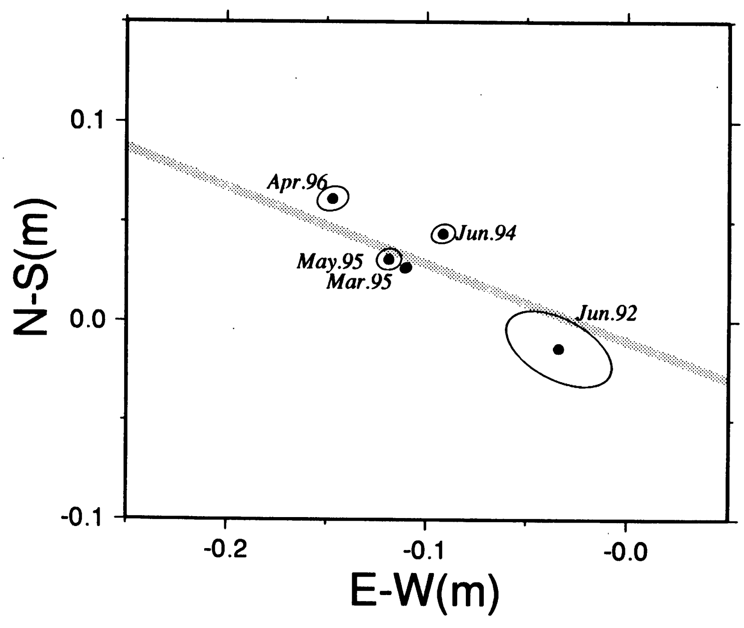

Fig. 3. Horizontal positions of Okino Torishima estimated for each GPS campaign and fitted linear trend.

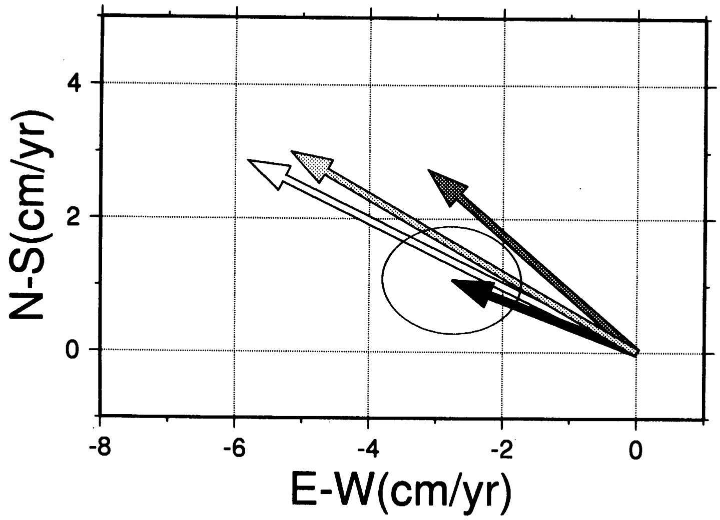

Fig. 4. Horizontal velocity vectors of Okino Torishima. (1) Black arrow is the estimated velocity assuming ITRF93 velocity at Tsukuba, (2) dark gray arrow is that assuming Tsukuba as stationary, (3) light gray arrow is that assuming Tsukuba moving toward west relative to stable Eurashian craton (Heki, 1996). 95% confidence ellipse is drawn for (1), while those for (2) and (3) are omitted for simplicity (see Table 2). Open arrow is the hypothetical velocity based on Seno *et al.* (1993)'s model.

1σ error ellipses. Linear fit to its position was also shown in the figure. Black arrow of Figure 4 is the vector representation of the velocity obtained above; that is, N68.7 (±16.1)°W with 2.97(±1.02)cm/yr. 95% confidence ellipse is also shown.

Then, in order to obtain relative displacements of Okino Torishima to Tsukuba, Tsukuba was resumed as stationary in the observation period by subtracting its ITRF93 velocity $(Vns, Vew) = (-1.65 \pm 0.15, 0.35 \pm 0.15)$cm/yr. The velocity of Okino Torishima in this assumption is $Vns = 2.73(\pm 0.82)$cm/yr and $Vew = -3.12(\pm 1.05)$cm/yr as is shown by a dark gray arrow in Figure 4.

Finally, velocity of Tsukuba relative to the stable Eurasian continent was estimated taking the results of Heki (1996) into account. Heki (1996) estimated the velocity at Tsukuba to be $Vns = 0.27(\pm 0.14)$ cm/yr and $Vew = -2.05(\pm 0.13)$cm/yr based on VLBI observations assuming velocities of several stable sites in the midst ofcontinental craton as representative rigid plate motions. We added these values to the above estimated Okino Torishima velocity and obtained $(Vns, Vew) = (3.00 \pm 0.84, -5.17 \pm 1.06)$cm/yr (Figure 4). These results are summerized in Table 2. The last one may be considered as an estimate of the Okino Torishima velocity relative to the stable Eurasian craton.

Figure 4 compares the present results with that of a plate motion model derived by Seno *et al.* (1993) who used slip vector orientations of interplate earthquakes. Seno *et al.* (1993) suggested that the Euler vector of the Philippine Sea plate relative to the Eurasian plate is (48.23°N, 156.97°E, and 1.085 deg/m.y.). The estimated velocity at Okino Tori-

Table 2. Velocity estimates at Okino Torishima.

Case	Vns	Vew	Direction	Velocity	Assumption
(1)	1.08±0.81	−2.77±1.04	N68.7°W	2.97	Tsukuba as ITRF93
(2)	2.73±0.82	−3.12±1.05	N48.8°W	4.15	Tsukuba as stationary
(3)	3.00±0.84	−5.17±1.06	N59.9°W	5.98	Heki (1996)'s velocity
(4)	2.87	−5.81	N63.8°W	6.48	Seno *et al.* (1993) model

Unit: cm/yr

shima based on this Euler vector is (*Vns*, *Vew*) = (2.87 cm/yr, −5.81 cm/yr) (Figure 4). This figure shows that the observed displacements in the recent several years are well consistent with the plate motion averaged over a longer time scale. The result obtained by GPS may represent instantaneous plate motion of the Philippine Sea plate relative to the Eurasian plate and the island moves steadily at least during the recurrence time of interplate earthquakes which is hudreds of years. In other words, it is likely that Okino Torishima represents rigid motion of the Philippine Sea plate.

4. Discussion

Recent VLBI analysis suggests that the northeastern part of Japan is undertaken by the intraplate deformation (e.g. Heki, 1989, 1996). Other studies suggest that the northeastern Japan is lying not on the North American plate (NA) but on an independent platelet, referred to as Okhotsk plate (e.g., Savostin *et al.*, 1983, Seno *et al.*, 1996). Thus in the present study, we compared three assumptions as to the motion of Tsukuba; (1) assuming the velocity given by ITRF93 framework (*Vns*, *Vew*) = (−1.65±0.15 cm/yr, 0.35±0.15 cm/yr), (2) assuming Tsukuba as stationary, and (3) assuming Tsukuba as moving toward west relative to the stable Eurasian plate according to the recent VLBI results (Heki, 1996), which gives (*Vns*, *Vew*) = (0.27±0.14 cm/yr, −2.05±0.13 cm/yr). The last assumption may well be consistent with otherwise determined plate motion model as is seen in Figure 3.

Since the Japanese islands are in the plate boundary zone and are expected to be rapidly moving with at least a few cm/yr rate everywhere, it may not be good to assume any of site in the Japanese islands as the fixed site or reference site. Recent establishment of nationwide GPS permanent array clearly demonstrate this (e.g. Miyazaki *et al.*, 1995). Other sites that are located in the stable craton, where the motion is well established may have to be used as the reference site. Although, in the present study, Tsukuba was used in the baseline analysis, the obtained results were converted so that it refers to the stable Eurasian continent.

Recent studies have shown that the displacement rates of islands in the Philippine Sea plate derived from space geodetic techniques are in general consistency with plate motion models. Matsuzaka *et al.* (1991) first revealed using VLBI data that the displacement of Chichi Jima is consistent with the NUVEL-1 plate motion model (DeMets *et al.*, 1990). Disaster Prevention Research Institute *et al.* (1994) suggested that the displacement rate of Minami Daitojima relative to Okinawa, which was assumed to be on the Eurasian plate (EU), for the period from 1990 to 1993 is consistent with Seno *et al.* (1993). Yu and Chen, (1994) and Kimata *et al.* (1994) also estimated the PH-EU motion. Although these estimates including the present study are independent each other with different assumptions on reference datum and, moreover, with the different observation periods, these results suggest that the Philippine Sea plate is moving as a rigid block in the recent years, at least in the first order approximation.

However, consistency between conventional plate motion models and space geodetic data may have to be re-considered because plate motion models such as Seno *et al.* (1993) was constructed by indirect and inaccurate data at plate boundaries where rigid nature of plates are not standing at all. Thus, consistency between them might be only accidental. In order to reconstruct rigid plate motions by estimating Euler vectors, only space geodetic data taken at plate interiors should be used, which, in turn, provides us with useful data to evaluate non-rigid motions near plate boundaries.

In order to directly derive plate motions from the space techniques in the western Pacific and the eastern Asia, wide and dense network is indispensable. IGS regional array, however, has vast vacant area in this region. Kato (1992) proposed the Western Pacific Integrated Network of GPS (WING) to augument permanent array in the region. Although the area has many problems for continuous GPS observation such as data communication, AC power, weather conditions etc, overcoming those problems may provide us with invaluable data set to reveal the contemporary tectonics of the Philippine Sea plate and surrounding region in space and in time.

5. Concluding Remarks

We have conducted a series of GPS observations at Okino Torishima together with other peripheral sites around the Philippine Sea plate. Assuming that Tsukuba site follows ITRF93 velocity field, the displacement rate of Okino Torishima was estimated to be $(Vns, Vew) = (1.08 \pm 0.81$ cm/yr, -2.77 ± 1.04 cm/yr), or toward N68.7($\pm$16.1)°W with the rate of 2.97($\pm$1.02)cm/yr. Assuming Tsukuba as moving toward west with velocity $(Vns, Vew) = (0.27 \pm 0.14$ cm/yr, -2.05 ± 0.15 cm/yr) taking Heki's result into account, estimated velocity of Okino Torishima relative to the stable Eurasian continent was $(Vns, Vew) = (3.00 \pm 0.84$ cm/yr, -5.17 ± 1.06 cm/yr) or 5.98 cm/yr toward N59.9°W. The comparison of this result with plate motion models using seismic slip direction demonstrates good consistency. Since Okino Torishima is located in the midst of the plate and the local deformation does not seem to be expected, its displacements may represent the rigid plate motion of the Philippine Sea plate.

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