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Horizontal Motion of Chichijima Derived from Satellite Laser Ranging Observations †

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Abstract

The horizontal velocity of Chichijima was obtained through the Satellite Laser Ranging (SLR) campaign observations carried out in 1988 and 1996 by the Hydrographic Department of Japan. SLR analyses were made with global data by combining multiple geodetic satellites, AJISAI, LAGEOS-I and-II. The velocity of Chichijima from the SLR positioning results was estimated both in local and global approaches : from the baseline change rate with Simosato, the permanent SLR station in Japan, and from arc length rates between global stations. The latter approach gave an absolute velocity of Chichijima based on the no net rotation system. Both results are consistent with the predicted values from the Philippine Sea plate motion model by Seno et al. (1993) obtained from the seismic slip vectors along the plate boundary. The result also agrees with those from other space geodetic techniques, VLBI and GPS observations.

Key words : Chichijima, SLR, Philippine Sea plate, plate motion, no net rotation system

1. Introduction

Chichijima is located in the Izu-Bonin Islands, generally considered to be on the Philippine Sea plate (PH) close to the boundary to the Pacific plate (PA) (See Fig. 1). Since the PH is mostly covered with the ocean, a direct measurement of the plate motion is possible only in the limited small off-lying islands such as Chichijima.

The motion of Chichijima was first reported by Matsuzaka et al. (1991) based on the Very Long Baseline Interferometry (VLBI) observation. They obtained the relative motion of Chichijima to Kashima, where the permanent VLBI observation is being carried on, by analyzing two-epoch campaign data with the interval of two years in 1987 and 1989. They concluded that the result was consistent with the predicted plate motion by the NUVEL-1 (DeMets et al, 1990) model.

Tsuji (1995) also discussed the motion of Chichijima based on the continuous measurements of the Global Positioning System (GPS). He showed that the observed relative motion to Tsukuba agreed well with that of Matsuzaka et al. (1991). He also compared the result with the predicted motion from the model presented by Seno et al. (1993).

The Hydrographic Department of Japan (JHD) has been continuing the Satellite Laser Ranging (SLR) observation since 1982 at the Simosato Hydrographic Observatory in Wakayama Prefecture, central Japan. It had also conducted campaign observations at off-lying islands or coastal areas including Chichijima to determine their precise positions during 1988-1996 primarily for the boundary demarca-

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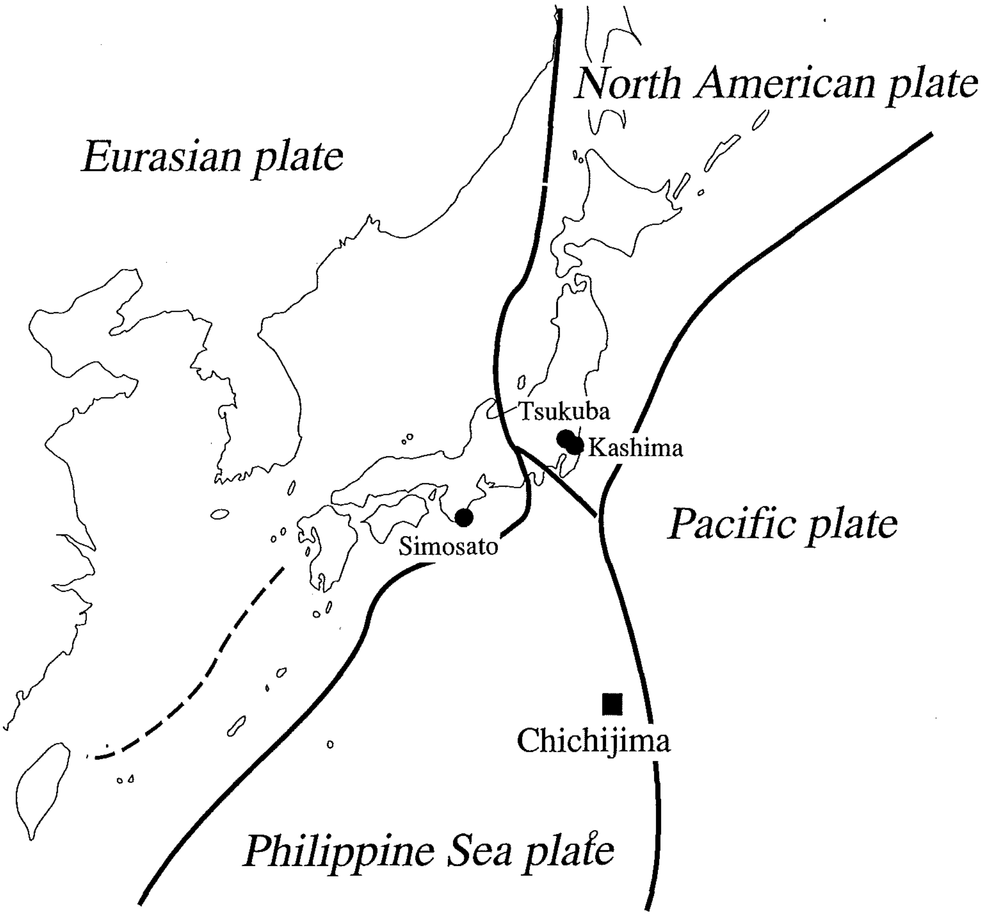

Figure 1. A map showing locations of observation sites. Chichijima and Simosato are the SLR sites of JHD. Kashima and Tsukuba are the permanent VLBI and GPS sites, respectively.

tion of the Japanese territory.

Second round observations in these campaign sites started in 1996 with Chichijima. The re-occupation at Chichijima made it possible to derive its motion through the SLR technique by comparing the two-epoch results. Although both the VLBI and GPS results above are based on the local baseline changes in Japan, the SLR can yield its absolute velocity in the global reference frame on the basis of the global analysis.

In this paper, we first present a relative velocity vector of Chichijima to Simosato based on the SLR analyses for the campaign observation periods in 1988 and 1996. Next, we give an absolute velocity vector of Chichijima in the no net rotation frame evaluated through arc lengths rates between global stations. We also compare the results with those obtained from the VLBI and GPS.

2. Observations

The first campaign observation at Chichijima with the mobile SLR station of the JHD called HTLRS (Sasaki, 1988) was carried out from January through March in 1988. The instrument was set on a stable ground in the NTT Yoakeyama relay station located in the northeastern part of the island. A stone marker, which is to remain permanently at the same point, was embedded about 30m apart from the instrument. An eccentricity survey was carried out between the measured point of the SLR instrument and the stone marker by a triangulation observation.

The second campaign observation was made from September through December in 1996, about eight and half years after the first one. The instrument was placed at almost the same site as in 1988. An eccentricity was also obtained with the triangulation survey.

3. Data

Used data are global normal points from three geodetic satellites. For the epoch of 1988, used satellites in analyses are the Japanese geodetic satellite, AJISAI, and the US geodetic satellite, LAGEOS-I. For 1996, data from LAGEOS-II, which has almost the same specifications as those of LAGEOS-I with slightly different orbit parameters, were also incorporated. Numbers of passes and normal points for Chichijima and Simosato used are listed in Table 1 together with those of global data.

Generally speaking, data from LAGEOS-I and-II are known to be preferable to those of AJISAI for the precise positioning because of their stable orbits. For the Chichijima observations, however, amounts of LAGEOS-I and-II data are not enough especially in 1988 due to some disadvantageous conditions of the mobile observation, whereas AJISAI data are abundant for both epochs because of its easy acquisition; this lead to an incorporation of AJISAI data into our discussion. We should point out that a recent development of geophysical models such as a geopotential field has made the precise positioning of AJISAI data quite reasonable (Sengoku, 1996 ; Fujita and Sengoku, 1997).

4. Analysis and positioning results

The geopotential model used for the analyses is JGM-3 (Tapley et al., 1994) with degrees and orders up to 22×22 for LAGEOS-I and-II and 70×70 for AJISAI. The atmospheric density model applied for the AJISAI analysis is MSIS86 (Hedin, 1987). The anisotropic reflection model (Sengoku et al., 1995) of AJISAI is also applied. The earth rotation parameters are fixed to the final values reported in the monthly bulletine of the International Earth Rotation Service (IERS Bulletine B). The parameters of ocean loading site displacement for the SLR stations are given from IERS Conventions (1996) (McCarthy, 1996).

In the station position estimation, the latitude and longitude of Maryland (NASA/GSFC) and the latitude of Hawaii (the Haleakala Observatory) are fixed to the global reference frame ITRF93 (Boucher et al.,1994). Since the ITRF93 coordinates are given at the epoch 1993. 0, the station positions are transferred to those of the observation epochs by use of the

Table 1. Data summary used in this study. The number of passes and normal points for Chichijima and Simosato are shown together with those of global data with numbers of the used stations.

epoch	Satellite	Chichijima		Simosato		Global		
		Pass	NP	Pass	NP	Stn	Pass	NP
1988 Jan. 21-Feb. 28	AJISAI	34	420	119	2381	16	517	9722
	LAGEOS-I	11	95	18	198	18	378	5498
1996 Oct. 1-Nov. 30	AJISAI	35	341	110	2117	32	2144	35162
	LAGEOS-I	12	74	36	390	34	1343	12652
	LAGEOS-II	26	262	51	709	35	1276	15624

ITRF93 velocity field.

In addition, it is assumed that Simosato data have a range bias of +7.0cm for both epochs, which has been generally reported. Note that the positive sign for the bias represents the longer observation of the range. For the mobile station employed at Chichijima, we also assume range biases of +1.7cm for 1988 and of +4.1cm for 1996, obtained from collocation observations with the fixed-type SLR stations at Simosato (Sengoku et al., 1997).

The strategy we took for this analysis is to combine all the satellite data, AJISAI, LAGEOS-I and-II, in the normal matrix level. The normal matrix for each satellite is produced based on the single arc analysis for the whole observation period shown in Table 1. The software used is GEODYN-II (Eddy et al, 1990) combined with SOLVE (Ullman, 1992) developed by National Aeronautics and Space Administration (NASA) of the USA. The GEODYN-II is used for producing normal equation matrices for respective satellites, and the SOLVE combines the resultant multi-matrices of normal equations and solves them to give the final station coordinates. Here, we combine equations from AJISAI, LAGEOS-I and-II with equal weights.

Estimated rectangular coordinates of Chichijima and Simosato from the SLR analyses for both epochs are shown in Table 2.

In order to investigate the movement of Chichijima between two epochs, it is necessary to make an eccentricity correction to the SLR-derived coordinates. Table 3 shows the eccentricities determined from the triangulation surveys for both epochs. Applying these values to the SLR-derived coordinates, we obtain the position of the stone marker, as shown in Table 2. Errors included in the eccentricities are supposed to be a few millimeters in the horizontal component and a little larger in the vertical component.

5. Velocity of Chichijima

In this section, we discuss the velocity of Chichijima derived from the SLR positioning results.

For this purpose, we first take a local approach, which uses the baseline change rate from the domestic reference site, Simosato. Since the determination of the single local baseline vector from the SLR global analysis is supposed to be fairly robust (Fujita and Sengoku, 1997), the resultant relative velocity is considered highly reliable.

However, the local approach discards the global information included in the SLR analyses. This lead us further to a global approach, which can estimate the absolute

Table 2. Estimated rectangular coordinates with formal errors of SLR measured points at Chichijima and Simosato together with those of the stone marker at Chichijima after eccentricity corrections.

epoch	position	X (m)		Y (m)		Z (m)	
1988	Simo SLR	-3822388.364	0.011	3699363.505	0.011	3507573.234	0.007
	Chichi SLR	-4491072.491	0.012	3481527.800	0.015	2887391.883	0.010
	Chichi Marker	-4491061.291		3481517.741		2887417.424	
1996	Simo SLR	-3822388.379	0.005	3699363.586	0.005	3507573.144	0.004
	Chichi SLR	-4491068.257	0.011	3481531.208	0.010	2887394.378	0.008
	Chichi Marker	-4491061.038		3481517.975		2887417.405	

Table 3. Eccentricity corrections at Chichijima.

epoch	NS (m)	EW (m)	UD (m)
1988	-29.576	-1.088	1.736
1996	-26.790	-6.036	1.810

velocity of Chichijima on the least squares scheme by using arc length rates between globally distributed SLR stations.

The following two subsections deal with these approaches independently together with some discussions based on comparisons with other studies.

5.1 Local baseline approach

We describe here the discussion of the local approach, which is based on the change rate of the baseline vector with Simosato.

Table 4 shows the baseline vectors between the SLR measured point at Simosato and the stone marker at Chichijima for both epochs and their difference. From the difference between the baseline vectors, the horizontal movement of Chichijima relative to Simosato is evaluated as 35mm/y with the azimuth of 292°. For later discussions, we should point out here that the local baseline results here is almost independent of the applied velocity field in the SLR positioning analysis, since the slight differences in the fixed coordinates does not affect the local baseline vector (Fujita and Sengoku, 1997).

Simosato, which is generally considered to be on the Eurasian plate (EU), has been reported to move relatively to the EU by about a few centimeters per year. For instance, Sengoku (1996) gave the velocity of Simosato relative to the EU as 32mm/y with the azimuth of 291° by comparing his result through 8-year analyses of AJISAI SLR data with the NUVEL-1model. This movement is usually interpreted as an inner plate deformation in the plate boundary region.

Here, we calculate the motion of Chichijima relative to the EU by combining our baseline rate of Chichijima to Simosato with the velocity of Simosato to the EU given by Sengoku (1996). This is done by transforming the Simosato horizontal movement to the rectangular components and adding to the baseline rate between Simosato and Chichijima, and finally projecting this velocity vector into the horizontal plane at Chichijima. The horizontal relative velocity of Chichijima to the EU thus obtained is 67mm/y with the azimuth of 293°.

Next, we compare the relative velocity of Chichijima to the EU with the plate motion models of the PH presented by Seno et al. (1993), which were obtained through seismic slip vectors at the plate boundary. In the paper, they gave two different models, a preliminary and a final models, from different geological boundary constraints. The preliminary model uses EU-PA relative motion of the NUVEL-1 model as a constraint, whereas the final model

Table 4. Baseline vectors with formal errors from the SLR measured point at Simosato to the stone marker at Chichijima and differences between both epochs. For the propagation of formal errors from the coordinates to the baselines, variance-covariance matrices for the SLR measured points are used for the stone marker instead at Chichijima.

epoch	dx (m)		dy (m)		dz (m)		baseline (m)	
1988	-668672.927	0.009	-217845.765	0.010	-620155.809	0.008	937642.516	0.009
1996	-668672.659	0.011	-217845.611	0.011	-620155.739	0.008	937642.243	0.011
Δ	0.268	0.014	0.154	0.015	0.070	0.011	-0.273	0.014

additionally satisfies the boundary constraints of the relative displacement between the Caroline plate (CR) and the PA estimated geologically. The predicted horizontal motion vector at Chichijima calculated from the preliminary model is 62mm/y with the azimuth of 295° and that from the final model is 49mm/y with the azimuth of 295°.

Fig. 2 shows the comparison of the velocity vectors determined by us and Seno et al. (1993). As seen from the figure, the vector obtained from the preliminary model without the CR-PA constraints agrees better with our results rather than that from the final model. It should be mentioned that, Tsuji (1995) also concluded that the relative velocity of Chichijima to the PA agrees better with the preliminary model of Seno et al. (1993) based on the GPS measurements. In this respect, our SLR result is consistent with the GPS result. A further comparison with the GPS result will be made later in this paper.

From Table 4, we can also obtain the vertical change rate of Chichijima relative to Simosato; it amounts to -8 mm/y. It should be noted, however, that there is still some ambiguity in the range bias problem in the SLR systems (Sengoku et al., 1997), which might cause an error in the vertical positioning; a further investigation on the range bias is necessary. Therefore in this paper, we only discuss the horizontal movement, which is not affected by the range bias significantly.

5.2 Global arc approach

In this subsection, we discuss the velocity of Chichijima evaluated from arc length rates between global SLR stations.

Method

An arc length along the earth surface between two stations is calculated by multiplying an angle between position vectors of two stations from the geocenter by the standard radius of the earth. We apply 6,378,137m as the radius of the earth. A discussion based on the arc length is on an assumption of the spherical earth approximation. Although the earth is generally approximated as an ellipsoid, a spherical approximation is enough here, because the flattening of the earth is about 1/300, which affects the results insignificantly in consideration of the precision of interest.

Arc lengths are calculated for all combinations of the global stations that have data both in 1988 and 1996. Stations whose data were

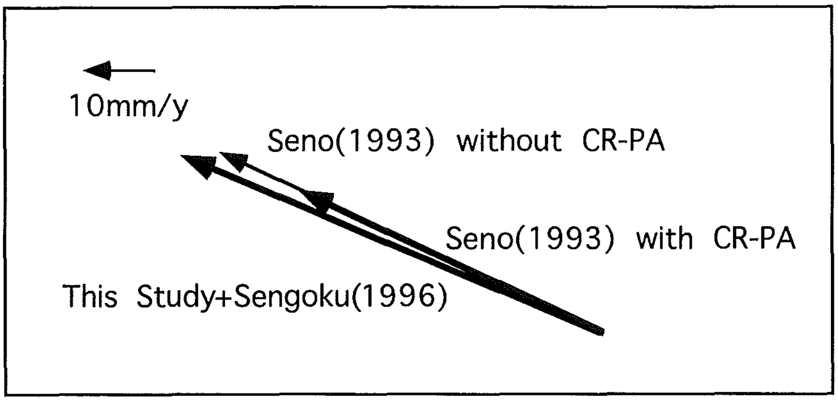

Figure 2. Relative velocity vector of Chichijima to the Eurasian plate obtained from the baseline change to Simosato in combination with the Simosato motion of Sengoku (1996). Those predicted from Seno et al. (1993) based on two different gelogical constraints are also shown for comparison. See the text for the two geological constraints in detail.

analyzed for both epochs are 11 stations: Maryland, Quincy, Monument Peaks and Hawaii in the United States, Yaragadee in Australia, Grass, Matera, Greenwich and Graz in Europe, Simosato and Chichijima in Japan. Although the number of the stations is limited, they include most of the historically significant SLR stations distributed globally. We obtained arc length rates between the 11 stations with the total number of arcs being 55.

An absolute velocity of Chichijima is determined from the arc lengths rates by applying the weighted least squares estimation scheme (cf. Sengoku, 1996). In the estimation, the velocities in the NS and EW components of Maryland and those in the NS component of Hawaii were fixed to the ITRF93N velocity field (Boucher et al., 1994). This combination of fixed components was chosen for the consistency with the position estimation.

The ITRF93N velocity field is different from the ITRF93 used in the position estimation only by a slight rotation to follow the time evolution of the NNR NUVEL-1A model (DeMets et al., 1994). This means that the ITRF93N is formed on the basis of the no net rotation system, whereas the ITRF93 is to be consistent with the IERS Earth rotation parameters. In this course, we use the term "the no net rotation system" as our absolute velocity field in the sense that it is consistent with the NNR NUVEL-1A model.

Absolute velocity

The absolute velocities thus estimated for all the 11 global stations are shown in Table 5 together with their formal errors and differences from the ITRF93N. It should be noted that comparatively large formal errors for Quincy are due to its extremely sparce data in 1996. The obtained velocity vector of Chichijima in the no net rotation system shown in Table 5 is 41mm/y with the azimuth of 281°.

In Fig. 3, the absolute velocity vector of Chichijima is compared with those calculated from Seno et al. (1993) incorporated into the NNR NUVEL-1A model. Again, it is seen that the estimated vector is close to that from the model without the CR-PA boundary condition, which is consistent with the result from the local baseline analysis.

For further comparison of the global result here with the local one in the previous subsection, we evaluate the velocity of Chichijima relative to the EU also from the absolute velocity. This is done by calculating a velocity vector at Chichijima from the NNR NUVEL-1A on an assumption that it is on the EU, and subtracting this from the absolute velocity. The resultant velocity is 65mm/y with the azimuth of 292°. Comparing this value with that in the local approach, we can conclude that the local and global approaches are consistent with each other. Just note that the velocity of Simosato by Sengoku (1996) used in the local approach is consistent with the NUVEL-1, whereas the obtained velocity here is based on the NUVEL-1A, which may not alter the conclusion.

Assessment of the two-epoch method

In this study, we used two-epoch data for deriving the global velocity field because of the campaign observations at Chichijima. Here we will see the reliability of this method by comparing with other studies that are considered comparatively robust.

First, we compare our estimated arc length rates with those obtained from the 10-year (1978-1988) LAGEOS-I data analysis made by Smith et al. (1990). Fig. 4 plots the arc rates between 10 global stations except Chichijima obtained in this study against those obtained

Table 5. Estimated absolute velocities for the global staions in the sense of the no net rotation system together with their formal errors and differences from the ITRF93N values. The velocities of NS and EW components at Maryland and NS component of Hawaii were fixed to the ITRF93N values in the estimation.

STN	NS (mm/y)			EW (mm/y)		
	VEL	SIG	DELTA	VEL	SIG	DELTA
Maryland	4.0	0	0	-13.9	0	0
Quincy	-4.7	3.5	1.3	-30.7	2.6	-11.2
Monument Peak	19.3	1.3	3.6	-37.1	1.1	3.9
Hawaii	35.0	0	0	-64.0	1.3	-3.9
Grass	8.6	1.8	-2.9	19.6	1.3	-2.4
Matera	11.9	1.4	-7.6	21.1	1.3	-3.2
Graz	4.4	1.5	-10.8	20.3	1.6	-3.7
Greenwich	9.0	1.3	-8.6	16.8	1.2	-1.9
Yaragadee	58.5	1.1	2.6	41.3	1.2	1.0
Simosato	-3.8	1.4	0.3	-8.0	1.2	-4.2
Chichijima	**10.3**	1.2	*	**-40.7**	1.8	*

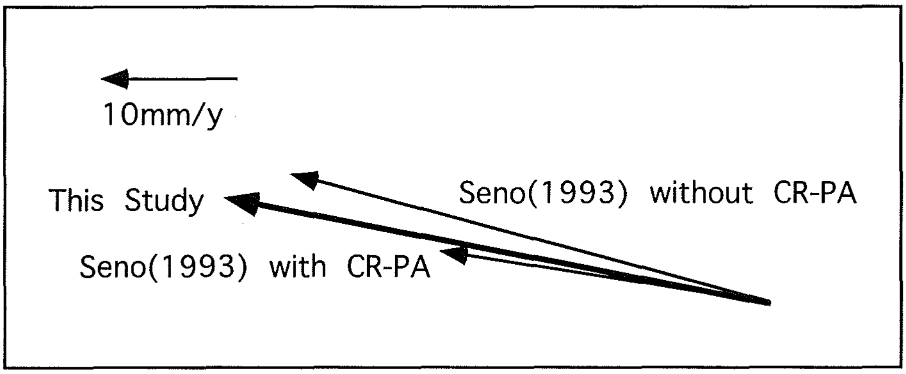

Figure 3. Absolute velocity vectors of Chichijima in the no net rotation system. Those predicted from Seno et al. (1993) based on two different geological constraints are also shown for comparison.

by Smith et al. (1990) together with their formal errors. Here again, plots that have extremely large error bars are from arcs including Quincy.

The linear adjustment between these two results gives a slope of 1.08±0.03 with the intercept on the ordinate of 1.70±0.90mm/y. A closer examination shows, however, that excluding the points of the Quincy-included arcs with large errors considerably reduces the deviation to 1.03±0.02 for the slope and to 0.63±0.84mm/y for the intercept. This indicates that they agree with each other except the Quincy-included arcs by about 3%, which implies that the difference is not more than a few millimeters per year level. We confirmed that Quincy-included arcs did not contaminate the estimated absolute velocities of the other stations because of the weighting scheme.

Next, we compare our global absolute velocities with the ITRF93N velocity field. Table 5 also shows the deviation of our estimations from the ITRF93N velocity field. The differences between our results and the ITRF93N except the fixed components and those of Chichijima are −2.8±5.2mm/y in the NS component and −2.8±3.9mm/y in the EW component.

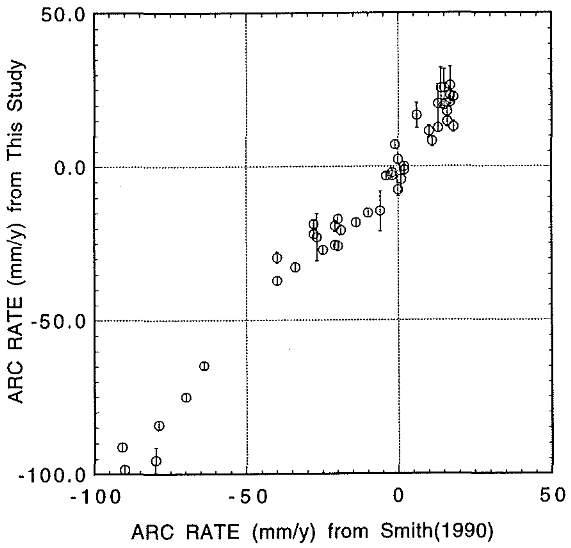

Figure 4. Comparison of Arc length rates obtained in this study with those from Smith et al. (1990). The slope from the linear adjustment is 1.03±0.02, excluding Quincy-included plots with extremely large error bars.

From these comparisons, we can conclude that the difference between our two-epoch results and the other results does not exceed several millimeters per year level both for arc length rates and estimated velocities, which can be regarded as one of the measures of an accuracy of our result.

Comparison with VLBI and GPS results

The motion of Chichijima has been also reported through the VLBI (Matsuzaka et al., 1991) and the GPS (Tsuji, 1995) observations. These results are derived as the relative motions to the domestic reference sites, Kashima for the VLBI and Tsukuba for the GPS, both considered to be located on the North American plate (NA) (See Fig. 1). Tsuji (1995) compares his GPS result with that of the VLBI by correcting the relative motions of the both reference sites to the NA obtained by Argus and Lyzenga (1993) independently. He concluded that they agreed well with each other.

In order to compare our results with those from the VLBI and GPS results, we also obtained the velocity of Chichijima relative to the NA by comparing the absolute velocity with the NNR NUVEL-1A model. Table 6 shows the velocity thus obtained together with those of the VLBI and GPS cited in Tsuji (1995).

Fig. 5 compares the relative velocity vectors to the NA between three techniques. As seen from this figure, they agree fairly well in the direction but differ by several millimeters per year in the magnitude ; the SLR-derived vector is a little larger than those of the VLBI and GPS. In consideration of the possible errors in the assumed motion of the reference sites for the VLBI and GPS and the accuracies of these techniques, we should conclude that these three results are consistent with each other.

6. Summary

The campaign observations with the Satellite Laser Ranging technique were carried out at Chichijima in 1988 and 1996 using a mobile station of the Hydrographic Department of Japan. Analyses of these data were made with the global SLR data by combining those from AJISAI, LAGEOS-I and-II. From the estimated positions for both epochs, we evaluated the velocity of Chichijima both in local and global approaches.

The estimated velocity of Chichijima relative to Simosato is 35mm/y with the azimuth of 292°. Combining this with the velocity of Simosato relative to the EU by Sengoku (1996), which is obtained through 8-year analysis of AJISAI, yields the velocity of Chichijima to the EU as 67mm/y with 293°.

On the basis of the arc length rates between the global SLR stations, the absolute velocity of Chichijima in the no net rotation system was

Table 6. Velocity vector components of Chichijima relative to the North American plate obtained from the SLR together with those from the VLBI and GPS.

Technique	NS (mm/y)	EW (mm/y)	Citation
SLR	27.4	-46.7	This Study
VLBI	23.5	-43.4	Matsuzaka et al. (1991) + Argus and Lyzenga (1993)
GPS	21.7	-40.0	Tsuji (1995) + Argus and Lyzenga (1993)

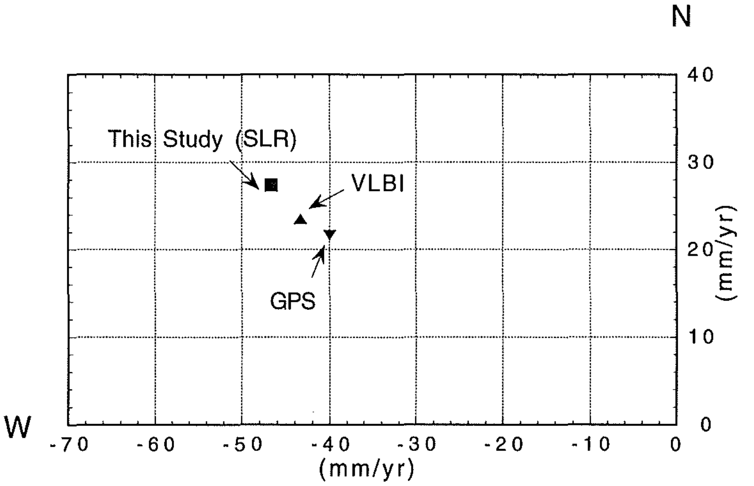

Figure 5. Comparison of the SLR result in this study with those of the GPS and VLBI. The plots indicate the velocity vectors of Chichijima relative to the North American plate shown in Table 6.

evaluated to be 41mm/y with 281°. An accuracy is considered to be several millimeters per year level.

Both local and global results are consistent with those predicted from the Philippine Sea plate motion model by Seno et al. (1993), which were derived from the seismic slip vectors in the plate boundary region. Our SLR result also agreed with those from the VLBI and GPS observations.

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References

Argus, D. F., and G. A. Lyzenga, Constraints on Interseismic Deformation at Japan Trench from VLBI Data, *Geophys. Res. Lett.*, **20**, 611-614, (1993).

Boucher, C., Z. Altamimi, and L. Duhem, Results and Analysis of the ITRF93, *IERS TECHNICAL NOTE*, **18**, (1994).

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current Plate Motions, *Geophys. J. Int.*, **101**, 425-478, (1990).

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of Recent Revisions to the Geomagnetic Reversal Time Scale on Estimates of Current Plate Motions, *Geophys. Res. Lett.*, **21**, 2191-2194, (1994).

Eddy, W. F., J. J. McCarthy, D. E. Pavlis, J. A.

Marshall, S. B. Luthke, L. S. Tsaoussi, G. Leung, and D. A. Williams, GEODYN-II System Operations Manual, Vol.1-5, *Contractor Report, ST Syst.Corp., Lanham, Md.*, (1990).

Fujita M., and A. Sengoku, Estimation of Baseline Vectors between First Order Control Points and Simosato Based on Analyses of AJISAI SLR Data (in Japanese), *Rep. Hydrogr. Res.*, **33**, 1-13, (1997).

Hedin, A. E., MSIS-86 Thermospheric Model, *J. Geophys. Res.*, **92**, 4649-4662, (1987).

Matsuzaka, S., M. Tobita, Y. Nakahori, J. Amagai, and Y. Sugimoto, Detection of Philippine Sea Plate Motion by Very Long Baseline Interferometry, *Geophys. Res. Lett.*, **18**, 1417-1419, (1991).

McCarthy. D. D., IERS Conventions (1996), *IERS TECHNICAL NOTE*, **21**, (1996).

Sasaki, M., Completion of a Transportable SLR Station of the Hydrographic Department, *Data Report of Hydrogr. Obs., Series of Satellite Geodesy*, **1**, 59, (1988).

Sengoku, A., New Surface Force Modelings on Artificial Satellites and Their Application to Analysis of 8-year Satellite Laser Ranging Data of Ajisai, *Doctoral Dissertation of the Graduate University of Advanced Studies*, (1996).

Sengoku, A., M. K. Cheng, and B. E. Schutz, Anisotropic Reflection Effect on Satellite, Ajisai, *Jour. Geod.*, **70**, 140-145, (1995).

Sengoku, A., M. Fujita, and N. Ikeda, Reanalysis of SLR Collocation Observations between SLR Stations (in Japanese), *Abstract of 88th Meeting of Geodetic Society of Japan*, 29-30, (1997).

Seno, T., S. Stein, and A. E. Gripp, A Model for the Motion of the Philippine Sea Plate Consistent with NUVEL-1 and Geological *Data, J. Geophys. Res.*, **98**, 17941-17948, (1993).

Smith, D. E., R. Kolenkiewicz, P. J. Dunn, J. W. Robbins, M. H. Torrence, S. M. Klosko, R. G. Williamson, E. C. Pavlis, N. B. Douglas, and S. K. Fricke, Tectonic Motion and Deformation from Satellite Laser Ranging to LAGEOS, *J. Geophys. Res.*, **95**, 22013-22041, (1990).

Tapley, B. D., M. M. Watkins, J. C. Ries, G. W. Davis, R. J. Eanes, S. R. Poole, H. J. Rim, B. E. Schutz, C. K. Shum, R. S. Nerem, F. J. Lerch, E. C. Pavlis, S. M. Klosko, N. K. Pavlis, and R. G. Williamson : The JGM-3 Gravity Model, *XIX General Assembly of the European Geophysical Society*, Grenoble, France, April, 25-29, (1994).

Tsuji, H., Detection of Plate Motions around Japan Based on Daily GPS Measurements, *J. Geod. Soc.*, **41**, 47-73, (1995).

Ullman, R. E. : SOLVE Program, NASA Contract *Report NAS5-29393, Task 503*, (1992).

人工衛星レーザー測距から求めた父島の水平運動（要旨）

1988年と1996年に水路部によって行われた２度の人工衛星レーザー測距（SLR）キャンペーン観測から，父島の水平運動を求めた．SLR 解析は，あじさい，ラジオス１，ラジオス２のグローバルデータを用いた多衛星解析によって行った．これらの SLR 測位結果から，ローカル法及びグローバル法を用いて父島の運動速度を推定した．ローカル法では，SLR 定常観測点下里との基線変化を，グローバル法では，グローバル局間の弧長変化を用いている．特にグローバル法では，非回転系に基づく父島の絶対速度が求められた．両結果

は，地震のスリップベクトルから得られた，Seno et al. (1993)のフィリピン海プレート運動モデルによる予測値と整合的である．また，これらは他の宇宙技術であるVLBIとGPSによる結果ともほぼ一致している．