Horizontal Movement of Marcus VLBI Station due to the Pacific Plate Motion

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Abstract.

Current motion of the Minami-Torishima (Marcus) Very Long Baseline Interferometry (VLBI) station has been measured over the last five years of Western Pacific VLBI Network (WPVN) experiments. The results of 16 independent sessions indicated its steady motion of the station in the horizontal projection plane. The velocity was estimated as 80.5 mm/year toward N67.5W in the IERS Terrestrial Reference Frame (ITRF92). High reliability and quality of the data obtained from WPVN experiments was demonstrated by the result that the horizontal movement of the Marcus station is consistent with a constant velocity linear motion.

1. Introduction

Minami-Torishima (Marcus) island lies at about 153°59'E 24°17'N in the Pacific Ocean. This small island gives us a rare opportunity to study the behavior of the Pacific Plate because there have been no other precise geodetic measurement sites in the northwestern region of the plate. 'Marcus' is the English name of Minami-Torishima and we will use Marcus as the name of this island hereafter. The Western Pacific VLBI Network (WPVN) is a five year project of regional geodetic Very Long Baseline Interferometry (VLBI) network by Communications Research Laboratory (CRL) and Shanghai Observatory of the Chinese Academy of Sciences.

The purpose of the project is to measure tectonic plate motions with two new VLBI stations at Marcus and Minami-Daitojima, abbreviated as Daito. These two new stations, along with the Kashima and Seshan stations, complete a compact lozenge shaped network as shown in Figure 1. Four major tectonic plates meet in this region and have complicated mutual interactions with each other. The configuration of WPVN has the advantage that each of four observation sites is located on each of these four tectonic plates, i.e. Kashima on the North American Plate (NOAM), Seshan on the Eurasia Plate (EURA), Marcus on the Pacific Plate (PCFC) and Minami-Daitojima on the Philippine Sea Plate (PHIL). Relative plate motions should be observed as changes of vectors connecting these four VLBI stations, which are called 'baseline vectors'.

The plate boundaries in Figure 1 are ideally shown as narrow lines and some may even argue with the location of these boundaries around Japan. However, as discussed by Gordon and Stein (1992), plate boundaries are better described as zones of active deformation with various widths. Kashima is in fact considered to be located in the region of deforming lithosphere. Heki *et al.* (1990) discussed the motion of Kashima VLBI station and showed its steady motion is a result of contraction of northeastern Japan. Seshan also moves relative to the Eurasian Plate as a result of the collision between the Indian continent and the Asian continent (Avouac and Tapponnier, 1993). Recently Heki and Koyama (1993) discussed the motion of the Seshan station determined from VLBI data. The result obtained from international VLBI experiments was consistent with the distribution of regional deformation in central Asian region estimated from slip rates of strike slip faults and convergence rates across thrust zones. One important consequence from these studies is that both Kashima and Seshan VLBI stations are moving with constant velocities for at least the time range over which VLBI experiments have been performed, even though they do not really lie on tectonic plates. The stable movements allow their site locations to be expressed by coordinates which are linearly changing with time. This can be confirmed from their small uncertainties in site coordinates and velocity components in the terrestrial reference frame ITRF92 (International Earth Rotation Service : IERS, 1993). Kashima and Seshan VLBI stations have advantages among many VLBI stations distributed worldwide because numerous VLBI experiments have been performed involving them with various international VLBI networks. These stations are two of the 10 VLBI stations specified as 'Primary' sites for ITRF92 outside the United States of America. Thus, site positions of the other two stations in WPVN, Marcus and Daito, can be determined in the globally defined reference frame from baseline vectors to Kashima and Seshan estimated from geodetic VLBI experiments.

Through five years of WPVN project from 1989 to 1993, the site position of a 10m antenna at Marcus VLBI station has been repeatedly measured in 16 observing sessions. In this paper, we describe these experiments, concentrating only on Marcus sessions performed under the WPVN project, and discuss the movement of Marcus VLBI station estimated by analyzing these data.

2. VLBI Facilities for MARCUS

At the Marcus site, a new Az/El type antenna with a 10m diameter was constructed at the isolated coral reef island in 1989. This antenna is equipped with X and S-band receivers so that precise ionospheric delay correction is possible. These receivers are mounted at its cassegrain focus position (X-band) and at the prime focus position of the main reflector (S-band) separately. This was achieved with a Frequency Selected Subreflector (FSS), which reflects radio wave at the X-band frequency while it is transparent at the S-band frequency.

Since the Marcus station is not permanently attended by dedicated personnel, all the VLBI observation equipment, including a frequency standard system and a data recording system, were transported to the site each year from CRL. The K-4 Data Acquisition System (Kiuchi *et al.*, 1991; Hama and Kiuchi, 1991) and Crystal-Cesium frequency standard system (Kiuchi *et al.* 1989) proved their advantage of compactness in such operations where transportation is inherent. This frequency standard system is based on a highly stable quartz oscillator which has sufficient frequency stability at short time interval (< 200 seconds) to maintain coherence at X-band. Since the quartz lacks long term frequency stability, a Cesium Beam frequency standard system is utilized and overall frequency output is controlled by a Phase Locked Loop (PLL) circuit. Advantages of the system compared with a Hydrogen maser system which is usually used for geodetic VLBI experiments are its small size and light weight. However, it is less stable than a Hydrogen maser system so that the experiments had to be designed carefully to incorporate its characteristics. A new transportable Hydrogen maser system CH1-75 was used in the three sessions in 1993 instead of the Crystal-Cesium system. In 1989, a K-3 data recorder was used instead of a K-4 recorder in later years.

3. Experiments

All the experiments performed at the MARCUS station are summarized in Table 1. Once the necessary VLBI equipment was transported to the site, at least two experiments were performed there. Every year except 1989 the site was occupied in late June considering the calm weather conditions at the site. Because the experiments were done in the same season, any kind of seasonal fluctuations of systematic error are expected to be reduced when motions of VLBI sites are discussed.

At the Kashima site, the 34m antenna was used except for experiments in 1989. The 26m antenna was used in 1989 and 1990. Each year, two sessions were scheduled as regular series with a three station (Kashima, Seshan and Marcus) configuration. Five additional experiments were scheduled with a two station (Kashima and Marcus) configuration in 1991. Another experiment with a five station (Kashima, Seshan, Kokee, Fairbanks and Marcus) configuration was also organized in 1993. Since the Fairbanks station participated in the first experiment in 1990, there are two baseline length data for the Fairbanks-Marcus baseline, whereas there is only one baseline length datum for the Kokee-Marcus baseline.

Observation schedules for WPVN experiments were generated at Kashima Space Research Center of CRL. The software SKED developed by Goddard Space Flight Center (GSFC) was used for this purpose. For sessions held in 1989-1992, the observation scan length was kept short (ranging from 150 to 196 seconds) because the frequency stability of the Crystal-Cesium system does not remain good for longer integration times. Because of this restriction, only strong radio sources were chosen. For the sessions in 1993, each observation scan length was determined to satisfy a certain signal to noise ratio, 20 and 15 for X and S band respectively, with given flux density of radio sources. In addition, SKED was revised by GSFC to incorporate the capability to generate schedule files automatically by optimizing estimation of desired parameters. We optimized the schedules to minimize the estimation errors for Marcus site position by using this new function for the sessions in 1993.

Experiments were basically successful but some portions of sessions were lost for various reasons. A special case was that the S-band phase-cal signal was affected by spurious radiation from the X-band phase-cal system. It prevented S-band data taken in 1989 sessions from being used for bandwidth synthesis. To solve this problem, the phase-cal signal phase in each frequency channel was fixed to its average value. Although this procedure improved the data for the 1989 sessions, their quality is worse.

4. Processing and Analysis

Data processing was done mainly at Kashima Space Research Center, CRL following the procedure described by Kondo *et al.* (1992). The K-3 type correlator was used for the correlation. The software KOMB was used for the bandwidth synthesis. Two of the experiments were processed at Haystack Observatory using a Mark-3 correlator because the data recorded at Fairbanks and Kokee stations were recorded using Mark-3 high density recorders.

After the correlation, the data have been analyzed using the software CALC (Version 7.6) and SOLVE (Ryan *et al.* 1993). The IERS standards (McCarthy, 1992) were adopted in the model calculation. Actual site coordinates in the terrestrial reference frame (ITRF92) and radio source coordinates in the celestial reference frame (ICRF92) were obtained from the annual report of IERS (IERS, 1993). ITRF92 is composed of site coordinates at a time epoch (1988.0) and velocities, and hence, site coordinates in this reference frame at specific dates of experiments were calculated. Ocean loading coefficients for vertical and horizontal site displacements due to ocean tides at Marcus station were provided from Scherneck (1991). Earth Orientation Parameters (EOP) before 1992 were obtained by interpolating five day interval values described in the annual report of IERS (IERS, 1993), and from monthly reports of IERS (IERS Bulletin B) for experiments in 1993. In both cases, normal values of

UT1−UTC without any correction were used and these data were interpolated after short time tidal variation of UT1−UTC were compensated by a tidal variation model described by McCarthy (1992).

Station positions for Kashima, Seshan and Fairbanks stations were fixed to their *a priori* values. Only the Marcus and Kokee station positions were estimated. Clock offsets between stations were estimated as linear functions with breaks every 3 hours. The dry component of tropospheric zenith delay was determined from ground observations of meteorological data and the rest of the tropospheric delay, which is regarded as a wet component, was estimated in the same way as for clock offsets.

5. Results and Discussion

5.1. Results

Estimated baseline lengths along with their standard deviations are shown in Figure 2 for three baselines to the Marcus station. Two data for a baseline between the 26m antenna at Kashima (Kas26) and Marcus are included in the Kas34-Marcus (Kas34 : 34m antenna at Kashima) baseline data by subtracting 307.645m which is the difference of lengths between these two baselines according to the ITRF92 coordinates at 1988.0. A least squares estimate was applied to obtain an epoch value and a rate of change for each baseline. Table 2 shows these results and the expected rates of baseline length change from NUVEL-1 plate motion model (DeMets *et al.* 1990). These model estimations were obtained by assuming Kashima and Seshan are moving with the North American Plate and Eurasia Plate motions respectively.

To obtain the horizontal motion of the Marcus station, estimated coordinates from each session were converted to a locally defined reference frame. We chose ITRF92 coordinates of Marcus at 1988.0. as the origin and horizontal north, east and vertical zenith directions as three axes of the frame. Then these results in each component were again linearly fitted by linear least squares, as for the baseline length data. Results are shown in Figure 3. Epoch values at 1991.0 and rates of change for three components are tabulated with reduced Chi-Square values from the least squares estimations in Table 3. According to these results, the horizontal movement of the Marcus station is 80.5 mm/year toward N67.5W. Figure 4 shows the same results by 1σ ellipses projected onto the horizontal plane.

5.2. Effect of fixed positions of more than one station

Usually in a geodetic VLBI experiment analysis, only one station is chosen as a reference and its position is fixed throughout the analysis, whereas the other station positions are estimated. This is because reliably accurate *a priori* station positions are not available other than from VLBI itself. However, the main purpose of the present paper is to estimate the Marcus station position as accurately as possible. Since the number of VLBI experiments at Marcus and Kokee stations are limited, we considered it to be preferable to estimate coordinates of only these two stations, while fixing the other station positions to their *a priori* coordinates given by ITRF92. To confirm that this procedure is effective in improving the accuracy of estimation, analyses were repeated by fixing only one set of station coordinates and the results were compared. In the analyses here, one of the Kashima stations was selected as a reference. The results are summarized in Table 4. As expected, estimated rates from two different analyses are not significantly different for all three baselines. A point to be mentioned is the difference of RMS residuals for the Seshan-Marcus baseline. Since this baseline is the least sensitive baseline in the network, obtained time delay measurements have poorer uncertainties compared to the other baselines. If the station position of Seshan is fixed in an adequate manner, the poor baseline sensitivity does not necessarily degrade the Marcus station position estimate since the Kashima-Marcus baseline data are expected to function as strong constraints. On the other hand, if Seshan's position is allowed to be adjusted as in the case of latter analysis (2) in the Table 4, its estimated position may be offset from the true value by more than ITRF92 site position. Such a fit may thus degrade the repeatability of Seshan-Marcus baseline length estimates. The position estimates for Marcus station will also be degraded; this can be confirmed by the fact that the uncertainties of estimated rates of baseline lengths in case (2) in Table 4 are also larger than in case (1).

5.3. Data quality

As shown in Figure 2, the lengths of Kas34-Marcus and Seshan-Marcus baselines are well represented by linear function of time. Although the vertical position of the Marcus station has a large uncertainty and scatter as is usual for geodetic VLBI measurements, horizontal components have small uncertainties and their fits to the least square estimates of line are very good too. Values of reduced χ^2 in Table 2 and Table 3 can be used to evaluate the quality of the least square estimate. For Seshan-Marcus baseline length data, where the number of degrees of freedom is 8, 90% of distribution for reduced χ^2 is between 0.34 and 1.94, whereas for Kas34-Marcus baseline length data and three components of Marcus station position data, where 14 degrees of freedom, the distribution is between 0.47 and 1.69. All values obtained in this study are in these ranges. It suggests two things. First, the assumption that the Marcus station is moving linearly with a constant velocity is correct within the present uncertainties of estimates. Second, the estimated uncertainties of data are consistent with the repeatability of measurements.

Residual RMS values can be considered to represent repeatability of the obtained data. From these values, horizontal components of the Marcus station position and baseline lengths were determined with 1-2cm of uncertainty, whereas the vertical component was determined with 6cm of uncertainty. It is also seen that data from sessions in 1989 are poorer than the other years. This is considered as an effect of a problem in S-band phase calibration signal at Marcus station we experienced in 1989.

5.4. Comparison with plate motion models

The ITRF92 reference frame was generated by constraining it to be consistent with the No-Net-Rotation (NNR) NUVEL1 plate motion model (Argus and Gordon 1991). Because these two reference frames are identical, our estimate of the horizontal movement of Marcus can be directly compared with the plate motion velocity calculated from the model. According to the NNR-NUVEL1 model, plate motion velocity of the Pacific Plate at Marcus is 74.4 mm/year toward N57.0W. Our estimate from this study is 80.5 mm/year toward N67.5W. The comparison is shown in Figure 5. The uncertainty in our horizontal velocity estimate is about 3 mm/year. The difference in speed is 6.1 mm/year, but they differ in direction by more than 10 degrees. This discrepancy in the direction causes 15.5 mm/year difference in velocity.

In Table 2, estimated rates of baseline length change are compared with values calculated from the NUVEL1 plate motion model. Since there are only two data for the Fairbanks-Marcus baseline, we will limit our discussion to the other two baselines. Part of the difference for the Seshan-Marcus baseline is considered to be due to a motion of Seshan with respect to the Eurasia Plate. If the velocity of the motion is assumed as 9.7 mm/year toward N119.7E as given by Heki and Koyama (1993), its contribution to the rate of Seshan-Marcus baseline is −8.5 mm/year. Hence the difference between our result and the model becomes 4.9 mm/year. Similarly, if Kas34 is assumed to be moving at 14 mm/year toward N60W with respect to the North American Plate (Heki *et al.* (1990), its contribution to the rate of Kas34-Marcus baseline is 13 mm/year and the difference between our result and the model becomes 7.6 mm/year. These comparisons suggest that Marcus is moving toward both Kas34 and Seshan faster than expected from the NUVEL1 model.

6. Conclusion

The movement of the Marcus station is evident in both the baseline length data and station positions projected on the horizontal plane. On the other hand, any vertical movement was not detected under our current limit of vertical position uncertainties. These data are consistent with the station moving horizontally with a constant velocity. The result also demonstrated high reliability and quality of the data obtained from WPVN experiments.

Comparisons between our results and plate motion models, NUVEL1 and NNR-NUVEL1, indicates small but probably significant discrepancies. Although careful consideration should be given to a proper motion of each station and treatment of different terrestrial reference frames to declare there is really a discrepancy, the movement of the Marcus VLBI station will no doubt contribute to a further study about the behavior of the Pacific Plate.

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Figure 1. Configuration of Western Pacific VLBI Network. Locations of Fairbanks station (Gilmore Creek Geophysical Observatory, Alaska) and Kokee station (Kokee Park Geophysical Observatory, Hawaii) are also shown. Thick lines indicate plate boundaries between four plates, i.e. EURA : Eurasia Plate, NOAM : North American Plate, PHIL : Philippine Sea Plate and PCFC : Pacific Plate.

Figure 2. Baseline length plots from WPVN experiments. Each point is plotted with 1σ error bar. Straight lines are results of least squares estimations by assuming a constant change of each baseline length. Two open circles in the Kas34-Marcus baseline indicate the data were actually calculated from Kas26-Marcus baseline lengths.

Figure 3. Station positions of Marcus expressed in a local reference frame. Origin of the frame is taken to the 1988.0 position of Marcus according to ITRF92. Each point is plotted with 1σ error bar. Straight lines are results of least square estimations by assuming a constant change of each component.

Figure 4. Estimated positions and their 1σ error uncertainties of the Marcus station are projected onto the horizontal plane. A straight line is drawn by using epoch values and rates of change for north and east direction component given in Table 3. This line expresses the estimate of horizontal linear movement of the Marcus station. Five dots on the line correspond to positions at 1 year interval from 1989.5 to 1993.5.

Figure 5. Velocity vectors of Marcus station in the horizontal plane (1) obtained by our analysis and (2) given by NNR-NUVEL1 model.

Table 1. List of VLBI experiments for the Marcus station

Date of Exp.	Participated Stations				
1989.7.24	Kas26[a]	Marcus	Seshan		
1989.8.12	Kas26	Marcus	Seshan		
1990.6.25	Kas34[b]	Kas26	Marcus	Seshan	Fairbanks
1990.6.30	Kas34	Kas26	Marcus	Seshan	
1991.6.27	Kas34	Marcus			
1991.6.28	Kas34	Marcus			
1991.6.30	Kas34	Marcus	Seshan		
1991.7.01	Kas34	Marcus			
1991.7.02	Kas34	Marcus			
1991.7.03	Kas34	Marcus			
1991.7.04	Kas34	Marcus	Seshan		
1992.6.27	Kas34	Marcus	Seshan		
1992.6.30	Kas34	Marcus	Seshan		
1993.6.24	Kas34	Marcus	Seshan		
1993.6.26	Kas34	Marcus	Seshan		
1993.6.28	Kas34	Marcus	Seshan	Kokee	Fairbanks

[a]Kas34 = 34m antenna at Kashima

[b]Kas26 = 26m antenna at Kashima

Table 2. Baseline lengths and rates of shortening

Baseline	Baseline Length on 1991.0 (mm)	Rate (mm/year)	Reduced χ^2	NUVEL1 model (mm/year)
Kas34-Marcus	1812578116.1±4.6	−76.9±2.9	0.736	−82.3
Seshan-Marcus	3270841112.6±6.3	−108.8±3.5	0.988	−95.4
Fairbanks-Marcus	5885336991.0±14.6	−25.1±11.3	⋯	−6.4

Table 3. Marcus station position and velocity

Component	Epoch value at 1991.0 (mm)	Rate of change (mm/year)	Reduced χ^2	Residual RMS (mm)
North direction	91.7±4.5	30.8±2.6	0.622	11.6
East direction	−213.3±4.1	−74.4±2.5	0.878	14.3
Upward direction	−24.9±15.6	−1.9±9.8	1.093	65.8

Table 4. Results from two different methods of analysis

Baseline		(1)	(2)
Kas34-Marcus	Rate (mm/year)	-76.90 ± 2.88	-77.03 ± 3.04
	Residual RMS (mm)	11.36	11.08
Seshan-Marcus	Rate (mm/year)	-108.83 ± 3.49	-111.03 ± 5.62
	Residual RMS (mm)	18.28	54.22
Fairbanks-Marcus	Rate (mm/year)	-25.07 ± 11.25	-25.72 ± 11.25

(1) Kashima, Seshan and Fairbanks stations are fixed

(2) Only Kashima station is fixed