Vol. 38 No. 3 *Journal of the Communications Research Laboratory* Printed in Tokyo, Japan *November 1991* *pp. 533 – 542*

IV. EXPERIMENTAL RESULTS

IV.3 GEODETIC RESULTS FROM DOMESTIC VLBI EXPERIMENTS (1) JEG SERIES

By
Jun AMAGAI

(Received on March 18, 1991)

ABSTRACT

The Communications Research Laboratory (CRL), in cooperation with the Geographic Survey Institute (GSI), has conducted geodetic VLBI experiments on the baseline between the Kashima 26 m antenna and the Tsukuba 5 m antenna to establish a standard baseline for Japanese geodetic VLBI. These experiments were held nine times from 1984 to 1990. This paper describes the geodetic results of baseline analysis performed in these experiments. Four different methods of analysis were applied to these experiments to determine the most suitable one for baseline calculation. It was found that the repeatability of the estimated position of Tsukuba station is affected by tropospheric conditions, and that there has not been any significant change in the Kashima-Tsukuba baseline vector in the last 6 years.

1. Introduction

The Communications Research Laboratory (CRL) and Geographic Survey Institute (GSI) have carried out a series of geodetic VLBI experiments on the 55 km baseline between Kashima (36.0N, 140.7E) and Tsukuba (36.1N, 140.1E). We call this series of VLBI experiments the Japanese Experiments for Geodesy (JEG).

The main purpose of JEG is to establish a standard baseline for Japanese geodetic VLBI. This baseline is short enough to compare the geodetic results obtained by VLBI with other conventional survey techniques(1), and it is not necessary for baseline analysis to take plate motion into account since both Kashima and Tsukuba station are on the same plate. On the other hand, this baseline is long enough to neglect any problems caused by a relatively small fringe rate(2). For these reasons, this baseline is considered suitable for the geodetic VLBI standard. This baseline was also used to test some innovative VLBI techniques such as a new type of frequency standard named X'tal-Cs(3) and a wave front clock(4), and to compare their performance with conventional VLBI techniques.

This paper describes geodetic results of JEG, which have been carried out once or twice a year since 1984.

2. Experimental Conditions

We have performed nine JEGs from 1984 to 1989 under almost the same experimental conditions.

Locations of the stations used for JEG are shown in Fig. 1. Antenna and receiver performances of the stations are listed in Table 1. As usual, the ionospheric delay in geodetic VLBI experiments can be corrected using the dual frequency receiving method. An S band signal was utilized only for this correction, and the baseline vector was estimated using the group delay derived from an X band signal. Down conversion systems with local frequencies 8080 MHz for X band and 2020 MHz for S band were adopted for each station. The K-3 data acquisition system(5), which is compatible with the Mk-III VLBI data acquisition terminal(6), was used to collect data, and the Hydrogen maser frequency standard developed by CRL and the Anritsu corporation was adopted to maintain coherence between each station's receiving system. The hardware configurations were almost the same as the intercontinental VLBI experiments conducted by the NASA Crustal Dynamics Project (CDP)(7).

Radio sources used for JEG are listed in Table 2. Because the antenna diameter of Tsukuba station is very small as compared with usual VLBI stations, relatively strong radio sources were selected to obtain

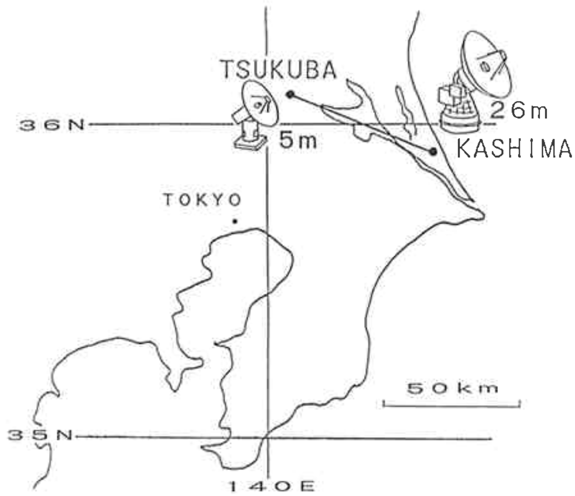

Fig. 1 Locations of JEG stations.

Table 1 Antenna and receiver characteristics

			X band		S bamd	
	Diameter	Mount type	Efficiency	Tsys	Efficiency	Tsys
Kashima	26 m	Az-El	53%	93K	52%	75K
Tsukuba	5 m	Az-El	72%	124K	30%	164K

enough correlated amplitude. In the first experiment (JEG-1), however we could obtain good fringes only for 47 observations since selection of the radio sources was not as good as originally thought. In the second experiment, radio source selection was improved by taking into account obtained source correlated flux. These radio sources included very extended ones such as 3C84 and 3C273B, which, although unsuitable for intercontinental VLBI experiments, can be used here since the Kashima-Tsukuba baseline is short enough so as not to resolve the radio source structure.

3. Analysis

Cross correlation processing for the data obtained by JEG was performed using CRL's K-3 correlation processor(5). Signal-to-noise ratios (SNR) of correlated data normalized to 100 seconds integration are listed in Table 2. It is found that the average of these normalized SNR's is greater than 20 for every experiment except JEG-1, where the source selection was inadequate as mentioned above. We derive the observed group delay and delay rate for both S and X band from the correlated data using a bandwidth synthesis technique(8). In this baseline analysis, we used only observed delay data because introducing observed delay rate data degrades the baseline analysis due to its low quality. Before baseline analysis, the dry component of tropospheric delay is removed from observed delay data using the Saastamoinen model(9) and the CFA mapping function(10) together with atmospheric data observed at each station. The CFA mapping function is also used estimating the wet component of tropospheric zenith delay. Cable delay correction is also applied to observed delay data.

Least square parameter estimation using the Cholesky decomposition method is employed for baseline analysis. This analysis is performed independently for each experiment on a ACOS computer. In these experiments, we treated Kashima station as a reference and estimated the position of Tsukuba station. We applied four types of methods to baseline analysis as shown in Table 3. Analysis #1 is thought to be the most suitable method based on our experiences. For this method, the epoch interval of estimation for the wet component of zenith tropospheric delay is set to 3 hours and applied to only the remote station (Tsukuba station). In addition, ionospheric delay is not corrected because the baseline length is thought to be short enough to consider ionospheric conditions for each station to be the same.

The other analysis methods differ from analysis #1 in the following points:

Analysis #2: Ionospheric delay is corrected.

Analysis #3: Epoch interval of estimation for tropospheric delay is set to 6 hours.

Analysis #4: Tropospheric delay is estimated for both Kashima and Tsukuba.

Epoch setting of clock parameters is the same for each experiment. Other estimation parameters are also the same for each experiment and each analysis method. Tropospheric delay change is estimated under a maximum constraint of 50 ps/hour. Station positions, radio source positions and Earth orientation parameters, which are used for calculation of a priori values, should be consistent throughout all experiments so as not to cause misleading variation among the experiments. The GLB401 solution(11) supplied by C. Ma and J. Ryan is used for station positions, radio source positions and Earth orientation parameters except for JEG-9, where different radio source positions are adopted for technical reasons. The difference between the radio source positions used for JEG-9 and those of the GLB401 solution is less than 4 milli-arc-seconds, and it is assumed that this difference affects estimated baseline vector components less than 1 mm. For the experiments performed after JEG-5, the values listed in the IERS weekly bulletin(12) were used for Earth orientation parameters because the GLB401 solution does not cover periods after 1987.

Table 2 Radio sources used for the JEG series experiments

EXP.	X band SNR for 100 sec. integration (Number of observations)									
SOURCE	JEG-1 84JUL18	JEG-2 85AUG08	JEG-3 86FEB17	JEG-4 87FEB23	JEG-5 88FEB09	JEG-6 88AUG25	JEG-7 89FEB22	JEG-8 89SEP29	JEG-9 90MAR01	Average
4C01.02	7.5(4)	12.5(4)	10.3(4)	13.7(6)	10.4(5)	8.6(6)		5.7(4)		10.0
0212+735		6.2(7)	8.0(3)							6.7
4C67.05	4.2(1)									4.2
0229+131				9.8(8)	7.1(8)	6.8(7)				7.9
CTD20				12.7(4)	18.3(4)	15.4(3)	19.9(7)	14.8(8)	14.0(8)	15.9
OD160	4.8(1)									4.8
3C84	49.9(1)	47.1(12)	96.5(9)	196.0(10)	123.4(11)	144.7(9)	153.3(8)	97.9(8)	115.0(11)	133.9
NRAO150	9.2(5)	16.2(12)	13.0(8)	44.8(9)	10.1(12)	10.0(10)	11.1(7)	9.0(10)	7.6(11)	14.5
OF247							14.7(5)	13.8(6)	12.6(7)	13.6
0454+844	5.7(2)									5.7
DA193	5.6(5)	10.7(9)	8.9(7)	22.6(8)	18.2(9)	18.5(6)	27.6(8)	27.0(8)	24.6(9)	18.8
0727-115							13.3(4)			13.3
0733-174	4.7(1)	4.7(2)								4.7
DW0742							11.6(6)	10.6(7)	10.3(7)	10.8
OJ287	5.2(6)	12.6(6)	8.7(8)	18.5(9)	13.2(8)	9.2(7)	13.0(7)			11.8
4C39.25	5.8(3)	13.2(13)	14.8(9)	27.0(11)	20.3(12)	23.9(10)	30.5(8)	29.0(10)	28.4(9)	22.3
3C273B	47.7(3)	17.8(12)	87.2(8)	122.3(9)	78.2(10)	75.4(7)	110.2(6)		109.5(8)	98.4
3C279		30.4(6)	22.0(7)	36.9(8)	34.2(7)	32.6(5)	42.4(5)	37.1(9)	38.0(7)	34.2
OQ208	4.2(2)	6.8(10)	10.0(5)	9.8(10)	7.5(4)	6.9(5)				8.0
1548+056				10.4(4)	7.1(3)	5.3(2)		6.2(8)		7.2
1642+690	0.0(0)									0.0
3C345	14.6(6)	32.2(10)	40.9(11)	42.1(12)	30.0(9)	25.2(7)	29.2(8)	23.2(10)	18.5(10)	29.7
NRAO530							25.3(7)	22.6(5)	24.0(8)	24.1
1803+784		10.3(8)	8.7(5)	11.3(14)	9.3(9)	12.4(12)	14.3(16)	11.5(13)	10.0(16)	11.3
OX057				33.2(9)	25.1(8)	25.9(8)		26.3(5)	23.0(7)	27.0
4C06.69				24.6(3)	21.9(3)	26.4(4)				24.5
VR422201		6.0(6)	8.3(5)			)				7.0
4C03.79			10.3(5)	9.9(7)	7.3(6)	6.7(7)				8.5
CTA102							11.7(7)	13.9(7)	11.5(8)	12.3
2243-123	4.7(2)	7.4(3)								6.3
3C454.3	19.5(5)	28.8(7)	35.2(8)	59.7(9)	46.2(10)	39.6(9)	48.3(7)	34.3(8)	28.5(8)	39.1
Average	12.2	37.3	30.1	42.6	31.7	30.2	35.6	24.3	31.8	
# of Sources	16	18	15	18	18	18	16	16	15	
# of Obs.	47	127	102	150	138	124	116	126	134	

Table 3 Conditions for baseline analysis and post-fit residuals

EXP.	DATE	Residual Delay [psec] (Number of observations used for analysis)				Number of clock epochs		
						Clk0	Clk1	Clk2
JEG-1	'84 JUL 18	98(46)	107(46)	111(46)	73(46)	3	3	0
JEG-2	'85 AUG 08	118(99)	148(99)	120(99)	113(99)	1	3	1
JEG-3	'86 FEB 17	74(98)	80(89)	77(98)	69(98)	2	5	0
JEG-4	'87 FEB 23	53(111)	71(84)	61(111)	50(111)	2	5	2
JEG-5	'88 FEB 09	87(114)	113(77)	91(114)	84(114)	3	5	2
JEG-6	'88 AUG 25	97(111)	134(85)	98(111)	90(111)	2	5	0
JEG-7	'89 FEB 22	97(107)	104(91)	100(107)	96(107)	1	5	0
JEG-8	'89 SEP 29	90(122)	94(109)	92(122)	87(122)	1	8	0
JEG-9	'90 MAR 01	73(126)	84(112)	75(126)	70(126)	2	5	0
Analysis #		#1	#2	#3	#4			
trop. epoch interval		3h	3h	6h	3h			
trop. station		remote	remote	remote	both			
Ion correction		off	on	off	off			

4. Geodetic Results of the Experiments

The estimated positions of Tsukuba station for each JEG are shown in Fig. 2. Weighted mean positions of the different set of experiments derived by each analysis method are shown in Fig. 3(A)–(C). From Fig. 3, we find that weighted mean positions of each analysis method agree with each other within one sigma error and the error ellipsoid for analysis #1 is rather small, as expected. Root mean square scatters of estimated position for analysis #1 are 7.2 mm, 6.2 mm, 39.9 mm and 7.5 mm for north, east, vertical component and length, respectively. Lower vertical sensitivity is thought to be caused by limits in the observed area of the sky. We can notice some differences in the estimated positions for each experiment from one analysis method to another.

In analysis #2, error ellipsoids became larger than those in analysis #1, by introducing the ionospheric delay correction as shown in Fig. 2. This indicates that ionospheric delay correction introduces only thermal noise into the delay observable and achieves no improvement in estimated position error for such a short baseline as Kashima - Tsukuba.

In analysis #3, Changing the epoch interval for the tropospheric zenith delay estimation does not introduce significant differences, in the estimated positions and errors. Consequently, tropospheric conditions can be regarded as stable within a period of less than 6 hours, at least near Kashima and Tsukuba.

In analysis #4, the estimated positions from the experiments agree well with each other except for JEG-1 (denoted by "A"), which lies apart from the rest. The reason of this is that the number of estimation parameters is too large to obtain a stable least square solution, especially for JEG-1 where the number of observations used for analysis is only 47 and the number of estimation parameters is 27. Error ellipsoids for analysis #4 where JEG-1 results are excluded (see Fig. 3(B)) are rather smaller than those including JEG-1, especially for the vertical component. However, it seems difficult to estimate the tropospheric zenith delay for each station because of a large mutual coupling between the zenith delay estimation at both sites. Actually, the estimated tropospheric zenith delay in analysis #4 was sometimes less than zero, which is physically impossible. The results of least square estimation under such an abnormal condition are not reliable and the apparently excellent results described above are considered to be only a coincidence.

Weighted mean positions of the experiments held during the winter season are shown in Fig. 3(C). We find that the error ellipsoids are smaller for every analysis method. The reason for this is considered

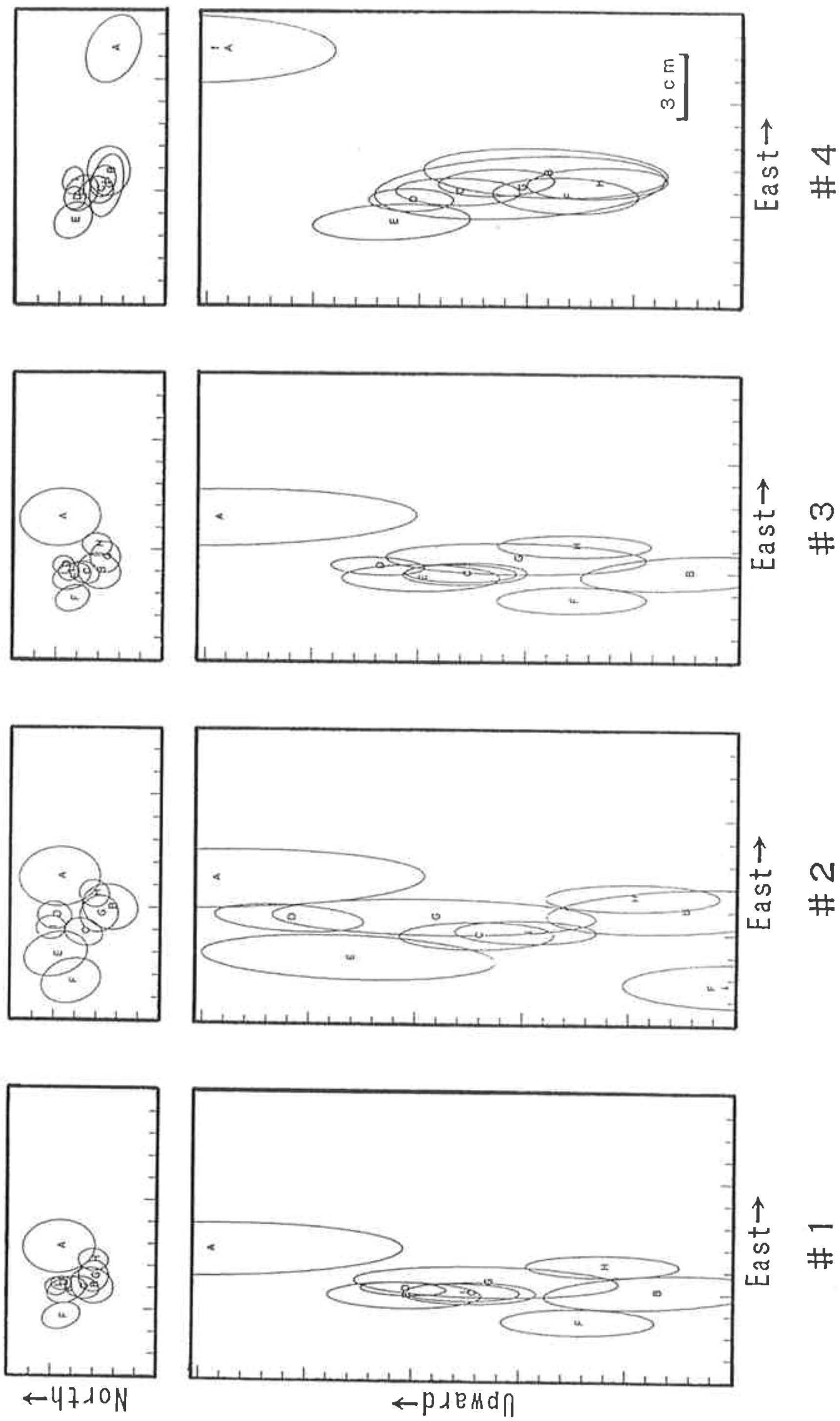

Fig. 2 **Relative position of Tsukuba station determined by each JEG shown in local coordinates. The letters A to I denote JEG1 to JEG9, respectively. Horizontal positions are shown in upper figure and vertical positions in lower figure.**

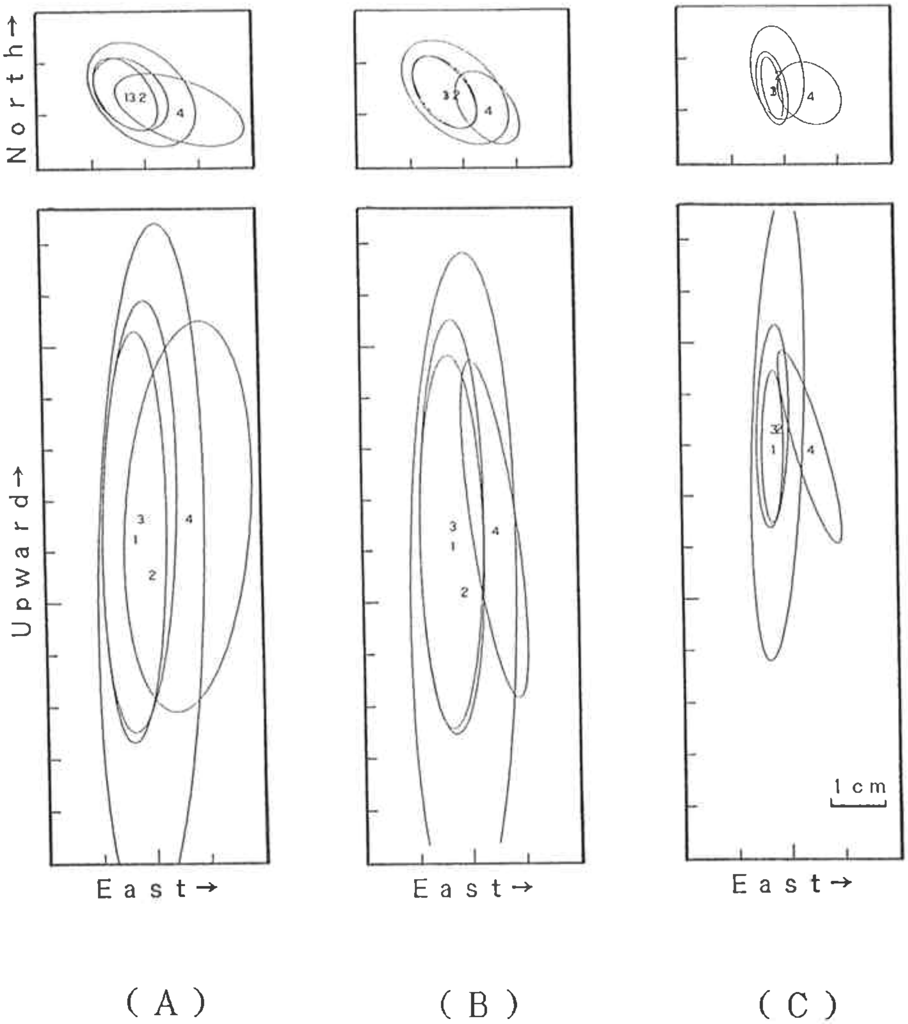

Fig. 3 Weighted mean position of the experiments derived by each analysis method shown in local coordinates. The population of (A), (B) and (C) is all experiments, all experiments except JEG1, and experiments held in winter season only, respectively. The numbers 1 to 4 denote analysis numbers.

to be the dry and stable tropospheric conditions of winter. Around Kashima and Tsukuba, the daily mean vapor pressure is usually around 5 mbar in winter but from 20 to 30 mbar in summer according to weather data obtained by the Japan Meteorological Agency. The estimated position for JEG's held in summer is thought to be affected by moist tropospheric conditions.

Figure 4 shows the Kai square value divided by degrees of freedom for each analysis method. For analyses #1 and #3, almost every component passed the Kai square test with a rejection standard (α) of

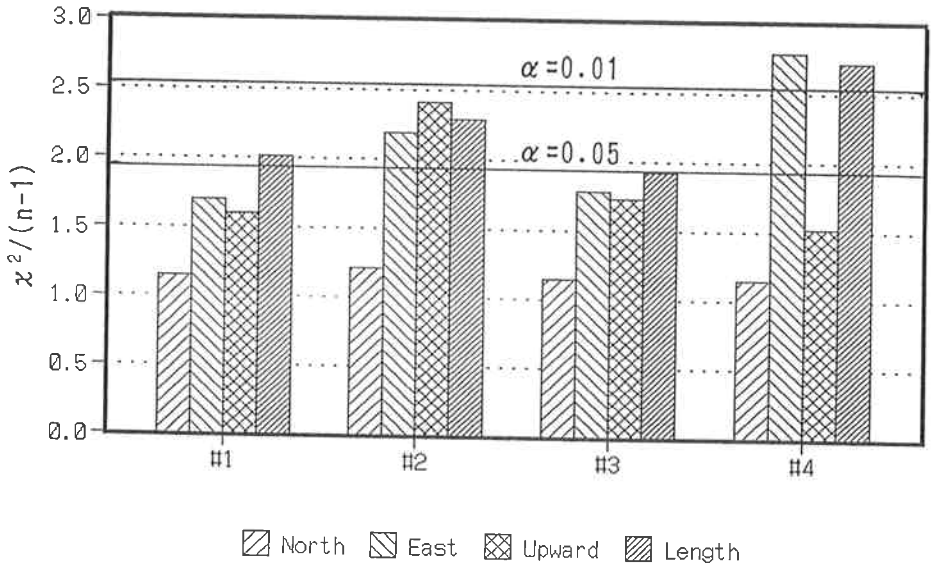

Fig. 4 Kai square value divided by degrees of freedom for each baseline component and length, where n is the number of experiments and α is the rejection standard.

Table 4 Weighted mean of each vector component and length of Kashima—Tsukuba baseline obtained by the analysis method #1

Population	Baseline Vector [m]			Baseline Length [m]
	X component	Y component	Z component	
All exp.	–40719.360 + 0.024	–33656.680 + 0.018	–13590.700 + 0.027	54548.560 + 0.008
Winter only	–40719.350 + 0.008	–33656.690 + 0.008	–13590.710 + 0.011	54548.560 + 0.004

0.05, showing that there are no systematic changes in estimated Kashima-Tsukuba baseline vectors.

Weighted mean of each vector component and length of Kashima—Tsukuba baseline obtained by analysis method #1 are summarized in Table 4.

5. Conclusions

JEG was held nine times from 1984 for the purpose of establishing a standard VLBI baseline in JAPAN. JEGs were performed under very similar experimental conditions and are suitable for comparison. We applied four types of baseline analysis to each experiment. Comparing the results obtained by each analysis method, we find that:

1) analysis #1 generated the best results;
2) ionospheric delay should not be corrected for the Kashima-Tsukuba baseline;

3) there is little difference between Epoch intervals of 3 hours and 6 hours for tropospheric delay estimation;

and

4) if the tropospheric delay is estimated for both stations, the geodetic results lack reliability.

Because the repeatability of geodetic results was better for experiments held in winter, the estimated position of summer experiments is considered to be affected by a moist troposphere. From the result of a Kai square test, it was found that there was not a significant movement of the Tsukuba-Kashima baseline vector and it was confirmed that this baseline is stable and suitable for the standard VLBI baseline of Japan.

In addition to the nine experiments described above we will continue to conduct JEG regularly two times a year. Future samples of data will provide a foundation for further statistical analysis regarding the geodetic results of JEGs.

Acknowledgments

The author thanks the staff members of Geographic Survey Institute. He also thanks Y. Sugimoto, H. Kunimori, N. Kurihara and M. Tokumaru who made great effort to conduct JEG Experiments. He is indebted to the members of the CRL VLBI project for their continuous guidance and encouragement.

References

(1) Kunimori, H., Kurihara, N., Kawaguchi, N., Takahashi, F., Yoshimura, Y., Saito, H., Hirabayashi, H., and Inoue, M.; "Geodetic VLBI Experiments Using Stations in Japan", J. Radio Res. Lab., **34**, 141, pp. 31, March 1987.

(2) Amagai, J., Kiuchi, H., and Kawaguchi, N.; "Short Baseline Experiments Using the Highly Transportable VLBI Station", IEEE Trans. Instrum. Meas., Vol. 38 No. 2, pp. 672–675, April 1989.

(3) Kiuchi, H., Amagai, J., and Kawaguchi, N.; "A Highly Stable Crystal Oscillator Applied to Geodetic VLBI", J. Commun. Res. Lab., Vol. 36, No. 148, pp. 107–124, Jul. 1989.

(4) Kiuchi, H. and Kondo, T.; "International VLBI experiment using the Wave front clock technique", J. Commun. Res. Lab., this issue.

(5) Kawaguchi, N., Sugimoto, Y., Kuroiwa, H., Kondo, T., Hama, S., Amagai, J., Morikawa, T., and Imae, M.; "The K-3 hardware system being developed in Japan and its capability", NOAA Technical Report NOS 95 NGS 24, Proceeding of Symposium No. 5, pp. 163, May 1982.

(6) Clark, T. A., Corey, B. E., Davis, J. L., Elgered, G., Herring, T. A., Hinteregger, H., Knight, C. A., Levine, J. I., Lundqvist, G., Ma, C., Nesman, E. F., Phillips, R. B., Rogers, A. E. E., Ronnang, B. O., Ryan, J. W., Schupler, B. R., Shaffer, D. B., Shapiro, I. I., Vandenberg, N. R., Webber, J. C., and Whitney, A. R.; "Precision Geodesy Using the Mark-III Very-Long-Baseline Interferometer System", IEEE Trans. Geosci. Remote Sensing, Ge-23, pp. 438–449, 1985.

(7) Coates, R. A. *et al.*; "Space-age geodesy: The NASA Crustal Dynamics Project" IEEE Trans. Geosci. Remote Sensing, vol. GE-23, pp. 360–368, July 1985.

(8) Rogers, A. E. E.; "Very long baseline interferometry with large effective bandwidth for phase-delay measurements", Radio Sci, Vol. 5, No. 10, pp. 1239–1247, Oct. 1970.

(9) Saastamoinen, J.; "Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites", The Use of Artificial Satellites for Geodesy, Geophys. Monogr. Ser., Vol. 15, edited

by S. W. Henriksen *et al.*, pp. 247–251, AGU, Washington, D.C., 1972.

(10) Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., and Elgered, G.; "Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length", Radio Sci., **20**, pp. 1593–1607, 1985.

(11) Ma, C., Ryan, J., and Caprette, D.; "Crustal Dynamics Project data analysis—1988", NASA, TM 100723.

(12) "IERS Bulletin", International Earth Rotation Service, weekly published.