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GEODETIC EXPERIMENTS USING THE HIGHLY TRANSPORTABLE VLBI STATION

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ABSTRACT

Communications Research Laboratory (CRL) has developed a highly transportable VLBI station (HTVS) using a 3 m antenna, with which geodetic VLBI experiments between Kashima and the HTVS at three different locations of Koganei, Wakkanai and Okinawa in Japan were carried out. In this paper, the results of the experiments are described. A different kind of frequency standard was used for each experiment. The ionospheric excess delays were compensated using the data observed at the ionosphere sounding stations in Japan. The precision of the determined baseline vector was compared with the result of trial using a 5 m diameter antenna, and a performance satisfactory for geodetic use was demonstrated.

1. Introduction

VLBI is one of the most precise measurement techniques for astronomy, astrometry, geodesy, and international time comparison(1). Usually a large fixed antenna, a high stability frequency standard, and a high density data recorder are necessary for geodetic VLBI experiments. Therefore the station layout is determined by the position of fixed antenna. However in order to measure regional scale crustal motion, mobile systems are required. In the U.S., a Mobile VLBI system known as MV, consisting of a trailer with a dish antenna, has already been put into service(2), but this system is too big to transport by road in Japan due to national traffic regulations. Thus we have developed a highly transportable VLBI station (HTVS). The system is characterized by its wider receiving band width for overcoming the degradation of the signal to noise ratio (SNR) of detected fringe due to the system's small antenna.

In 1987 and 1988 HTVS system performance tests were carried out with short baseline (80m) experiments(3). Thereafter in 1988 and 1989 geodetic experiments were performed between the Kashima station (36.0N, 140.7E) with the HTVS at three different locations in Japan, namely Koganei (35.7N, 139.5E), Wakkanai (45.4N, 141.7E) and Okinawa (26.3N, 127.8E). Three different kinds of time and frequency standards were used in these experiments, namely a fixed hydrogen maser, a highly stable crystal oscillator phase locked to a cesium frequency standard in a time range longer than 100s, and a transportable hydrogen maser.

The HTVS is equipped only with an X band receiving system. Because of this, it is impossible to calibrate the ionospheric excess delays directly as with usual dual band receiving systems. Hence the ionospheric delay was corrected using of the ionospheric data observed at the radiowave observatories located at Wakkanai, Akita (39.7N, 140.1E), Koganei, Yamagawa (31.2E, 130.6E) and Okinawa in Japan.

The baseline vectors were determined with a formal error of less than 1.5 cm for horizontal components by baseline analysis and the precision of baseline determination was compared with the result of the experiment with the 5 m diameter antenna mobile station of the Geographical Survey Institute (GSI).

In this paper we present the characteristics of HTVS, and outline of each experiment, and the results of baseline analysis. We also describe the method used for the ionospheric delay correction.

2. Highly Transportable VLBI Station (HTVS)

The HTVS is equipped with a 3 m diameter antenna to reduce the total weight and to allow high mobility (see Fig. 1). A small antenna is disadvantaged with regard to precise geodetic measurement, because the SNR of the fringe obtained by VLBI is in proportion to the product of two antenna diameters. In order to keep the SNR and the group dealy sensitivity the same as those of normal VLBI experiments, the total data band width (4Mbit × number of video bands) and effective band width (Root-mean-square of receiving frequencies) must be wider. To extend the receiving band width dual down converters are installed in the front end of the HTVS. Furthermore, the number of video channels utilized for X band group delay determination is increased by 6 to 14 compared with normal VLBI experiments as shown in Fig. 2.

Fig. 1 The HTVS 3 m antenna.

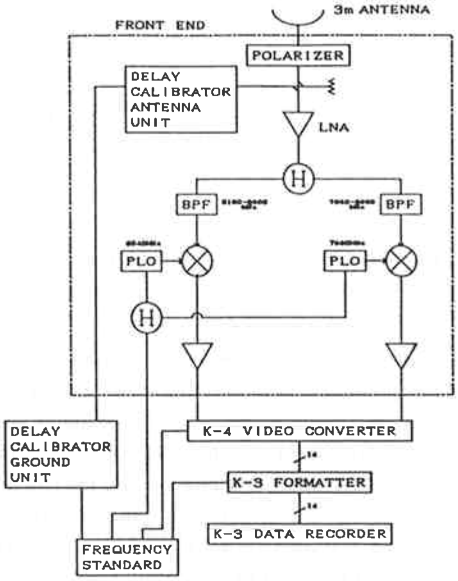

Fig. 2 System block diagram of the HTVS. In the geodetic experiments carried out in 1988 and 1989, only 10 of the 16 video bands were used due to hardware problem.

In case of normal geodetic VLBI experiments both S and X band signals are received for ionospheric delay compensation. However HTVS has only an X band receiving system because installation of dual band receivers with high efficiency in small antennas is difficult. The ionospheric excess delay was corrected using the ionospheric data observed at five ionosphere sounding stations at CRL radiowave observatories in Japan. The method used for the correction will be described later.

A compact VLBI data acquisition terminal developed by CRL called K-4 was adopted for the HTVS. This terminal consists of an IF distribution section, 16 video converters, and 16 local oscillators for the video converters. The arrangement of the local frequency for K-4 video converters is carefully chosen to avoid third harmonic interferences in the image rejection mixers, so that IF filters are not necessary for the IF distribution section and the size of video converter can be reduced. A K-3 data recorder(4) compatible with Mk-III data recorder(5) was used for data recording.

Two types of transportable frequency standard were used for the HTVS. One is the compact hydrogen maser frequency standard developed by CRL and Anritsu Corporation. To reduce weight the cavity of this hydrogen maser was made of aluminum. This compact hydrogen maser has a backup battery to maintain vacuum and cavity temperature.

The other is a new type frequency standard also developed by CRL which consists of a cesium time standard and a crystal oscillator. Here this system is referred to as X'tal-Cs(6). A crystal oscillator which is specially selected for its stability is phase locked to a cesium frequency standard in a time range longer than 100 s. When this frequency standard is utilized with a VLBI station, the integration time for each VLBI observation is limited to less than 120 s(6) (see Fig. 3). Therefore the SNR of the fringe will be smaller compared with the normal VLBI which are observed for a much longer time, and this frequency standard is unfavorable for use with VLBI stations having small aperture antenna such as the HTVS. However this frequency standard has the advantage of compactness, transportability, and low cost as compared with a hydrogen maser.

At a site where a fixed hydrogen maser is available, it is of course employed for the HTVS in addition to these two frequency standards.

The HTVS is carried on a 4 ton truck. Before loading on the truck, the 3 m antenna is separated into the main dish and the pedestal. The main dish is loaded on the truck in a tilted position as shown in Fig. 4.

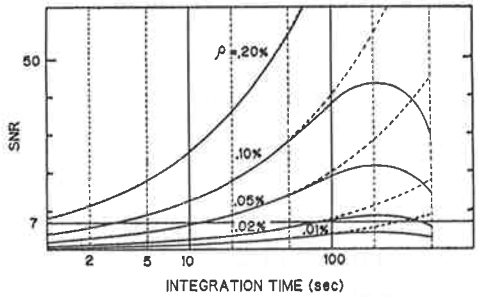

Fig. 3 SNR of the fringe obtained by VLBI with X'tal-Cs frequency standard.

Fig. 4 The 3 m antenna loaded on a truck.

3. Outline of Three Geodetic VLBI Experiments

In 1988 and 1989, three geodetic experiments using the HTVS were carried out at various locations in Japan. The experiments are summarized in Table 1. The locations of each station and

Table 1 VLBI experiment conditions

	Experiment Name		
	Koganei	Wakkanai	Okinawa
Date	'88 9/20	'88 10/5	'89 2/3
Baseline length	110 km	1051 km	1622 km
Freq. standard	High Stability H maser	X'tal-Cs	Transportable H maser
Integration time	200, 400 s	180 s	200, 400 s
Number of radio sources	16	6	14
Number of obs.	142	152	141
Number of Available obs.	108	80	99

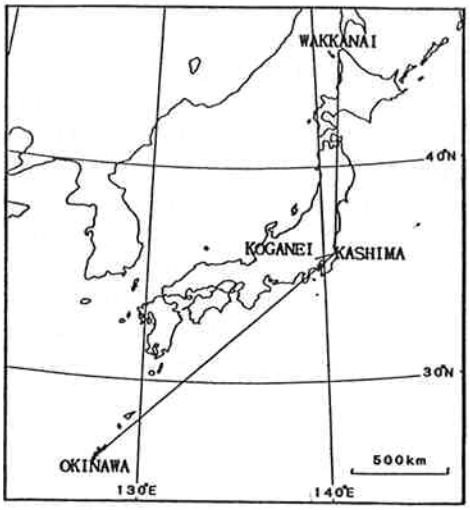

Fig. 5 Locations of the VLBI experiment stations.

the baselines are shown in Fig. 5. Each experiment is referred to in terms of the location of HTVS here.

3.1 Koganei Experiment

In September 1988, the HTVS was located at Koganei (35.7N, 139.5E). The first VLBI experiment was carried out on 110 km baseline between HTVS and Kashima 26 m antenna on September 20, 1988. The head quarters of CRL are located at Koganei, so the high stability hydrogen maser could be utilized as a frequency standard for the HTVS.

3.2 Wakkanai Experiment

The HTVS was relocated to Wakkanai (45.4N, 141.7E) in October 1988 and the second experiment was performed with Kashima on October 5, 1988. At that time the development of the transportable hydrogen maser was not completed, and so the X'tal-Cs was employed as the frequency standard of the HTVS.

3.3 Okinawa Experiment

After completing development of the transportable hydrogen maser, it was transported with the HTVS to Okinawa (26.3N, 127.8E) in February 1989 and the third experiment was carried out on February 3. Unfortunately the battery backup system of the transportable hydrogen maser had failed during transportation, and there was not enough time to recover the stability of the maser before the scheduled experiment. Because of this, the Okinawa experiment was carried out under imperfect frequency standard conditions.

4. Baseline Analysis and Ionospheric Correction

In this section we briefly describe the baseline analysis and also present the method for correcting the ionospheric excess delays. The data obtained by the VLBI experiments were correlated at Kashima using the K-3 correlation processor(4). After correlation processing, the baseline analysis was made for each VLBI experiment using obtained delay and delay rate data. In the Wakkanai experiment, the observed delay rate residuals were widely scattered compared with the other experiments because of the inferior stability of the X'tal-Cs. For this reason delay rate data were not used for baseline analysis. However this does not affect the analyzing results seriously because usually the contribution of delay rate data to the baseline analysis is relatively smaller than that of delay data(6). For other experiments, rate data were take into account.

In the baseline analysis, six parameters of HTVS were estimated using the least squares method(7). The estimated parameters were

1) station position (X, Y, Z)
2) clock offset and rate, and
3) zenith atmospheric delay (wet component).

In the Okinawa experiment the excess path delays caused by the ionosphere were corrected using the foF2 data observed at 5 radiowave observatories (Wakkanai, Akita, Koganei, Yamagawa and Okinawa) of CRL(8), because the Okinawa station is located in the region of so-called "equatorial anomaly" (e.g., Giraud and Petit(9)) of ionosphere and the ionospheric excess delays thought to be large. In the Koganei experiment, the baseline length is short enough for the effect of the ionosphere to be disregarded. In the Wakkanai experiment, for ionospheric delay correction was not made, as the ionospheric delay is thought to be relatively small due to the relatively high latitude of the stations.

The ionospheric excess pass delay is calculated as follows.

1) Calculate the total electron content (TEC) from foF2 data observed at the radiowave obsevatories using the empirical model that describes the relation between foF2 and TEC (AFCRL model(10)). This model is given as

$$\mathrm{TEC} = 1.24 \times 10^{13} (\mathrm{foF2})^2 \left\{ 261 + 26 \sin\left[\frac{(h-9)\Pi}{12} \right] + K \sin\left[\frac{(D-60)\Pi}{183} \right] \right\}$$

where

foF2: [MHz]

h: the local hour at the subionospheric point

K: 73 for $06 < h \leq 19$

K: 36 for $h = 05,20$

K: 0 for $21 < h \leq 04$

TEC: in electron/m^2

D: the day of year

2) Estimate the TEC at the subionospheric point of VLBI observation for each station from the TEC at 5 stations by using the linear interpolation or extrapolation for latitudinal direction, and the local time correction for longitudinal direction.

3) Calculate the excess pass delay from TEC taking into account the slant length for each station, and calculate the difference between two stations.

The subionospheric points of the VLBI observations for the Okinawa experiment are shown in Fig. 6. A mean ionospheric altitude of 300 km is assumed in the subionospheric point calculation.

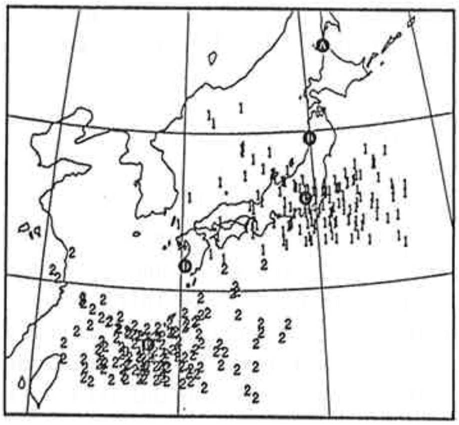

Fig. 6 The subionospheric points of the VLBI observations for the Okinawa experiment. Symbols "1" and "2" indicate the subionospheric points of the radio source observed from Kashima and Okinawa respectively. Radiowave observatories of CRL (A: Wakkanai, B: Akita, C: Koganei, D: Yamagawa, E: Okinawa) are also displayed in the figure.

The difference between the results of the baseline analysis before and after ionospheric delay correction is shown in Table 2. It was found that the baseline determination error and residual delay were improved. The improvement of residual delay was only 0.02 ns, but because the

Table 2 The results of the baseline analysis using the ionospheric delay correction and the result before correction.

	Estimation error				
	Baseline vector			Baseline length	Delay residual
Ion. correction	N-S	E-W	vertical		
not corrected	12 mm	11 mm	56 mm	15 mm	0.107 nsec
corrected	10 mm	10 mm	51 mm	14 mm	0.095 nsec

residual delay is calculated as the root sum square of errors, the contribution of ionospheric delay correction is estimated as 0.05 ns. This contribution is very large in comparison with the total delay residual of 0.1 ns.

5. Results and Discussions

The results of baseline analysis of three VLBI experiments are summarized in Table 3 and Table 4.

Table 3 Observed baseline vectors

	VLBI coordinate [m]		
	X	Y	Z
Koganei-Kashima	55814.886 ± .019	91750.862 ± .017	− 22213.418 ± .018
Wakkanai-Kashima	477835.826 ± .049	− 494757.840 ± .039	794096.600 ± .062
Okinawa-Kashima	1490116.713 ± .029	1244821.770 ± .037	− 916583.236 ± .024

Table 4 Summary of VLBI experiment results

	Experiment Name		
	Koganei	Wakkanai	Okinawa
Delay residual	0.072 ns	0.130 ns	0.095 ns
Delay rate residual	0.094 ps/s	0.868 ps/s	0.165 ps/s
N component error	0.6 cm	1.4 cm	1.0 cm
E component error	0.7 cm	1.0 cm	1.0 cm
U component error	2.9 cm	8.7 cm	5.1 cm
Baseline length error	0.5 cm	1.5 cm	1.3 cm

In the Wakkanai experiment, the precision of baseline determination was inferior to other VLBI experiments. This is thought to be due to the inferior stability of X'tal-Cs as compared with hydrogen maser. However the horizontal components of the baseline, which are important for measuring plate motion, were determined with a formal error of less than 1.5 cm.

In the Okinawa experiment, because the transportable hydrogen maser experienced considerable trouble as described above, the formal errors of the baseline components are larger compared with the Koganei experiment in which the high stability hydrogen maser was used for the frequency standard. If the experiment had been carried out with the transportable hydrogen maser in good working condition, the baseline would have been determined with almost the same precision as the Koganei experiment.

The result of the Koganei experiment was compared with the result of the VLBI experiment carried out on the 50 km baseline between Tsukuba mobile station using GSI's 5 m antenna and Kashima(11). The system performances are summarized in Table 5. The locations of these stations are shown in Fig. 7. The configurations of these experiments are very similar and the baseline lengths of both experiments are short enough to make baseline analysis without ionospheric correction, and so are suitable to evaluate the HTVS performance experimentally. Results of baseline analysis are summarized in Table 6. In the Koganei experiment the baseline length was determined with a formal error of 0.5 cm and the residual delay after baseline estimation was 0.072 ns.

Table 5 Performance of mobile VLBI stations

	Highly transportable VLBI station	Mobile station with 5 m antenna
Antenna diameter	3 m	5 m
Aperture efficiency	37 %	70 %
System noise temperature	120 K	124 K
Effective band width	273 MHz	124 MHz
Number of channels	10	8

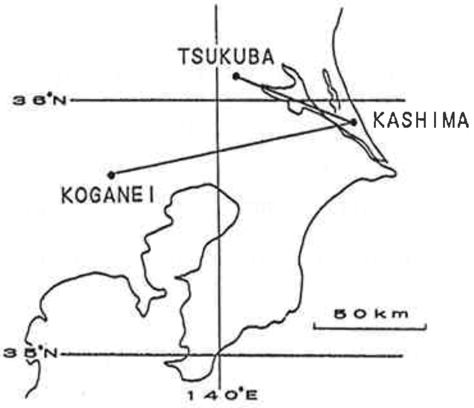

Fig. 7 The locations of the VLBI stations for Koganei-Kashima and Tsukuba-Kashima experiment.

From a comparison of the results it is found that the precision of baseline determination was almost same in spite of the antenna diameter difference. We can evaluate the expected precision of delay determination using the following relation(12),

$$\sigma_\tau \propto \frac{1}{D\omega_{\mathrm{RMS}}}\sqrt{\frac{T_{\mathrm{SYS}}}{\eta M}}$$

Table 6 The results of the experiments using two types of mobile stations

	Highly transportable VLBI station Kashima-Koganei 26 m 3 m	Mobile station with 5 m antenna Kashima-Tsukuba 26 m 5 m
Baseline length	110 km	55 km
Number of obs.	142	152
Number of Available obs.	108	118
Delay residual	0.072 nsec	0.079 nsec
Delay rate residual	0.094 psec/sec	0.081 psec/sec
X component error	1.8 cm	1.5 cm
Y component error	1.4 cm	1.2 cm
Z component error	1.5 cm	1.4 cm
Baseline length error	0.5 cm	0.4 cm

where

D; Antenna diameter [m]

η; Antenna aperture efficiency

T_{SYS}; System noise temperature [K]

ω_{RMS}; Effective receiving band width

M; Number of video channels

Substituting the parameters given in Table 5 into the above relationship, the precision of delay determination for the HTVS is expected to be improved by about 5% over that for the mobile station with a 5 m antenna. The results of the experiments were consistent with this expectation.

6. Conclusions

Three geodetic VLBI experiments were carried out between the HTVS and a 26 m antenna at Kashima in Japan. The baseline vectors have been precisely determined for all experiments.

Each of the three experiments used a different frequency standard, namely the fixed hydrogen maser, the X'tal-Cs, and the transportable hydrogen maser. By adopting the fixed hydrogen maser with high stability, it was demonstrated that the geodetic ability of the HTVS was comparable with the mobile station with a 5 m antenna. Even though the X'tal-Cs frequency standard for the geodetic use is inferior to that of the hydrogen maser, the horizontal components of baseline vector were determined with sufficient precision to measure the plate motion of several cms a year over a few years, and so the validity of X'tal-Cs for geodetic VLBI experiments is thought to be proved. However the actual performance of the transportable hydrogen maser frequency standard could not be evaluated because of problems experienced before the experiment. On the other hand, ionospheric delay correction by means of the foF2 data was successfully used for the baseline analysis.

In 1988, a 34 m antenna was constructed at Kashima for the purpose of geodetic VLBI experiments. The sensitivity of the VLBI is in proportion to the product of the antenna diameters employed in the observations, so it is assumed that an antenna whose aperture size is smaller than 2.5 m is acceptable for pairing with this new antenna.

Plans to carry the HTVS to Minami-Daito Island which is located in the south-west part of Japan on the Philippine sea plate, and make VLBI experiments with the Kashima 34 m antenna and Shanghai 25 m antenna are being made. The results of these experiments over the next few years will show the relative motion of Philippine sea plate.

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