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SPECIAL ISSUE OF THE CRL JOURNAL ON "WESTERN PACIFIC VLBI NETWORK"

By
Akira SUGIURA

1. Introduction

The Japanese Islands lie on four major tectonic plates, that is, the North American, the Eurasian, the Pacific, and the Philippine Sea plates. Taking advantage of this location, the Communications Research Laboratory (CRL; formerly the Radio Research Laboratory) has carried out many international Very Long Baseline Interferometry (VLBI) experiments since early 1980's. One of the best results was the precise initial detection of the Pacific plate movement which was accomplished in collaboration with various observatories in the USA.

Using this valuable experience, CRL initiated a new VLBI project named the "Western Pacific VLBI Network Project," in 1987. This project aimed to establish a domestic VLBI network with three stations located on different plates in order to investigate the regional crustal movement in the area of Japan. A 34 m parabolic antenna was constructed at Kashima (supposedly on the North American plate), and two 10 m-class antennas were constructed, one on Minamidaitojima Island (on the Philippine Sea plate) and the other on Minamitorishima Island (on the Pacific plate). The VLBI experiments in this project were conducted from 1989 to 1993 fiscal year with the participation of the Shanghai Observatory of the Chinese Academy of Science which served as the reference station on the Eurasian plate. This project produced many fruitful results concerning the relative motion of the plates around Japan.

In parallel with this project, CRL has carried out various other VLBI experiments and radio-astronomical observations. For instance, the "Metropolitan Diamond Cross Experiments" have been performed with the VLBI stations of the Geographical Survey Institute in Japan to investigate the crustal deformation in the Tokyo area. It is fearfully anticipated that great earthquakes will hit this huge city in the near future. Therefore, regular monitoring of the crustal deformation is considered to be of major importance in order to predict earthquakes. In connection with this, CRL has recently started the "Key Stone Project" which involves constructing four stations around the metropolitan area which will carry out regular VLBI and SLR observations.

This special issue will summarize the system development and experimental results of the Western Pacific VLBI Network Project and some related recent activities in CRL.

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II. OVERVIEW OF THE EXPERIMENT SYSTEM

II.1 THE MAIN VLBI STATION AT KASHIMA

By
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ABSTRACT

The Western Pacific VLBI Network was mainly organized by the VLBI stations of Communications Research Laboratory (CRL), Kashima, Marcus Island and Minamidaito Island, and Shanghai of China. The 34 m antenna built at CRL's Kashima Space Research Center (KSRC) in 1988 has been used as the main station of the Western Pacific VLBI Network. This antenna was constructed as one of the largest antennas in Japan and its main purpose is precise geodesy. It has many advanced functions for this purpose but was also designed for multipurpose observations. It is therefore also the main tool in precise space and time measurement projects, such as the earth rotation measurement VLBI, millisecond pulsars timing observations, and radio astronomical observations.

Keywords: VLBI (Very Long Baseline Interferometry), geodesy, plate motion, antenna

1. Introduction

The Communications Research Laboratory (CRL) has, since the middle of 1970s, been engaged in a study of Very Long Baseline Interferometry (VLBI) and international and domestic VLBI observations. The main observation tool for this study was the 26 m antenna which was built in 1967. This antenna was built for the experiments of satellite communications using 4/6 GHz bands, but was modified for VLBI experiments such as the US-Japan VLBI experiments for the NASA's Crustal Dynamics Project. Many remarkable results in the field of space geodesy[(1)-(4)] were obtained using this antenna but the research fields were expanded by constructing a new high-performance antenna (higher sensitivity and higher receiving bands) at Kashima Space Research Center.

A 34 m antenna made by TIW company in USA was introduced in 1987, and its construction was completed in 1988. The main project using this antenna is the "Western Pacific VLBI Network

*National Astronomical Observatory

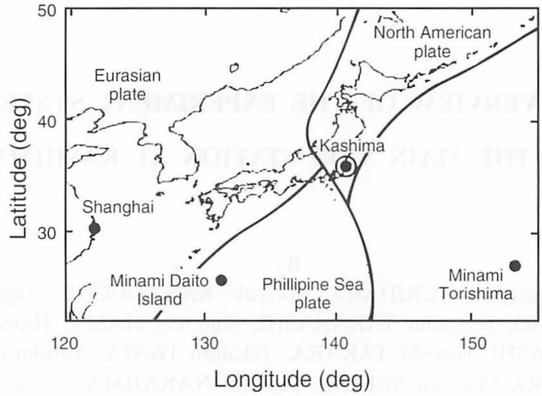


Fig. 1 Locations of the Western Pacific VLBI Network stations

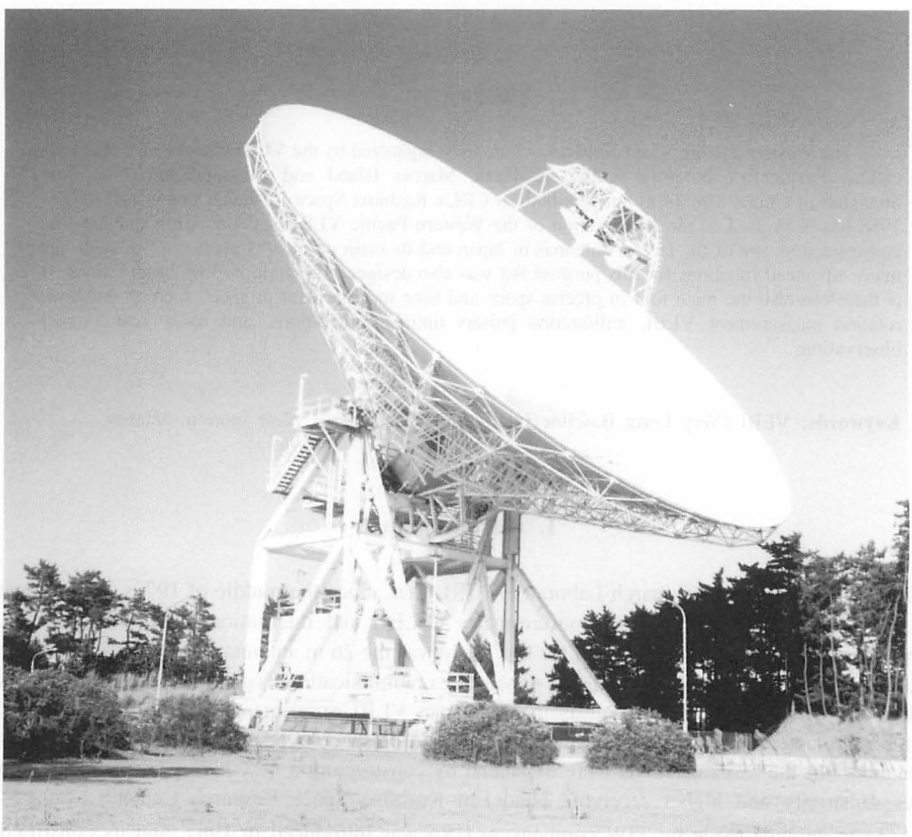


Fig. 2 Overview of the Kashima 34 m antenna

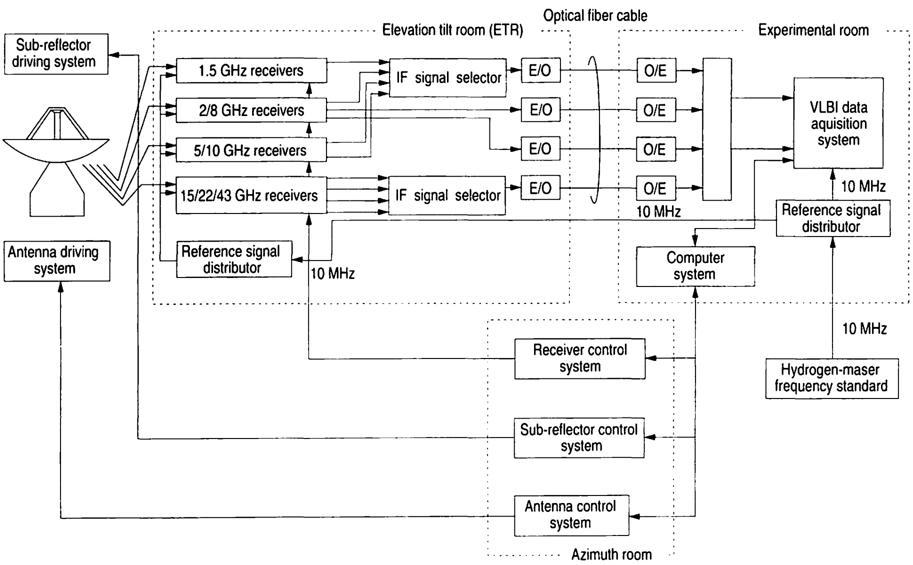


Fig. 3 Block diagram of the 34 m antenna system

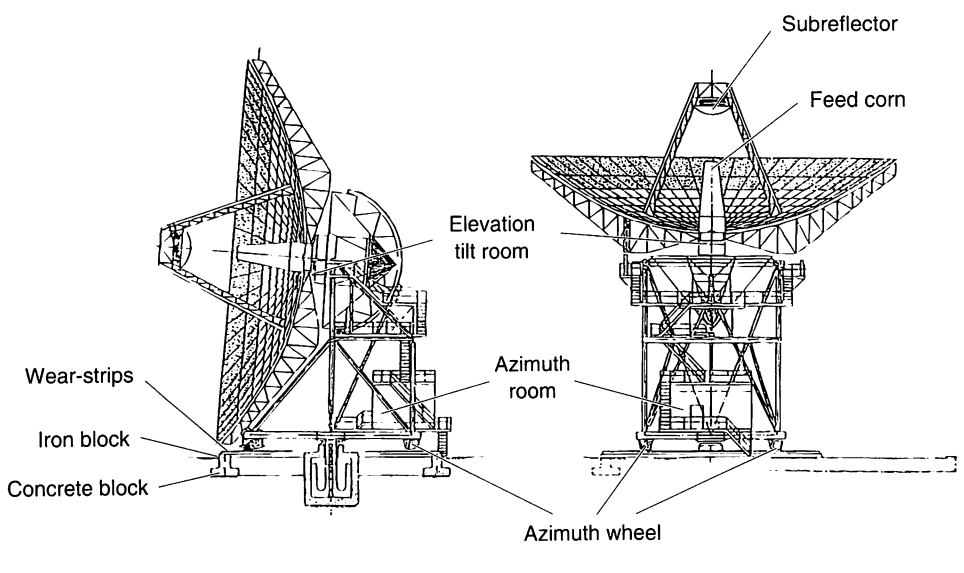


Fig. 4 Structure of the 34 m antenna

experiments," which was started in 1988 and is the main subject of this special issue. The main purpose of this project is to precisely measure the movements of the four main plates around the Japanese Islands in order to obtain the basic data for long-term earthquakes forecasts.

The main VLBI station of this project is the 34 m antenna at Kashima Space Research Center on the North American plate. At two stations on the Pacific plate and Philippine Sea plate, CRL placed a

Table 1 Mechanical specifications of 34 m antenna

Location	35°57′05.76″ N 140°39′36.16″ E
Antenna type	Cassegrain type
Mount type	Az-El mount
Aperture	34.073 m
Surface accuracy	0.17 mm (rms)
Diameter of the subreflector	3.8 m
Agreement of azimuth and elevation axis	<1 mm
Mounting style	Az-El mount
Driving speed	
Azimuth	0.7 degree/sec
Elevation	0.7 degree/sec
Drive range	
Azimuth	±359°
Elevation	6–90.7°
Subreflector moving range	
X-axis	±60 mm
Y-axis	±60 mm
Z-axis	±60 mm
Subreflector rotation range	
Around X-axis	±3.5°
Around Y-axis	±3.5°
Total weight	400 tons
Pointing resolution	1.235″

medium size VLBI station and a small transportable VLBI station[5]. The fourth station, on the Eurasian plate, is the Shanghai station which belongs to the Shanghai Observatory of Chinese Academy of Science. Figure 1 shows the locations of the VLBI stations of this project. The Western Pacific VLBI Network experiments were performed from 1988 to 1993.

The 34 m antenna was designed as a multipurpose antenna, and is used for many purposes in addition to the Western Pacific VLBI Network experiments. This paper gives an overview of the 34 m antenna system.

2. Kashima 34 m Antenna

This antenna (Fig. 2) has a parabolic type main dish and it's aperture size is the third largest in Japan. (The largest antenna is the Institute of Space and Astronautical Science's 64 m antenna at Usuda, and the second largest is the National Astronomical Observatory's 45 m antenna at Nobeyama.)

The basic design of this antenna is similar to those at the JPL (Jet Propulsion Laboratory) deep space tracking stations in California, Spain, and Australia, but many aspects were designed specially

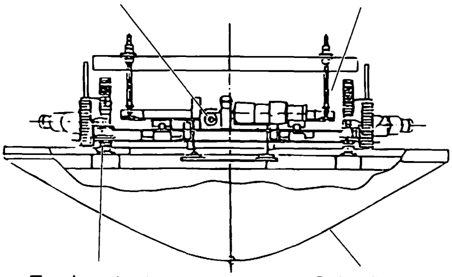


Fig. 5 Structure of the subreflector of the 34 m antenna

for the Kashima 34 m antenna. A simplified block diagram of the 34 m antenna system is shown in Fig. 3. The main features of this antenna are:

1) the high surface accuracy of main dish which can be used for millimeter wave observations,
2) multi-receivers system from 1.5 GHz band to 43 GHz band.

In this section we show the main performance and specifications of the 34 m antenna.

2.1 Mechanical Specifications

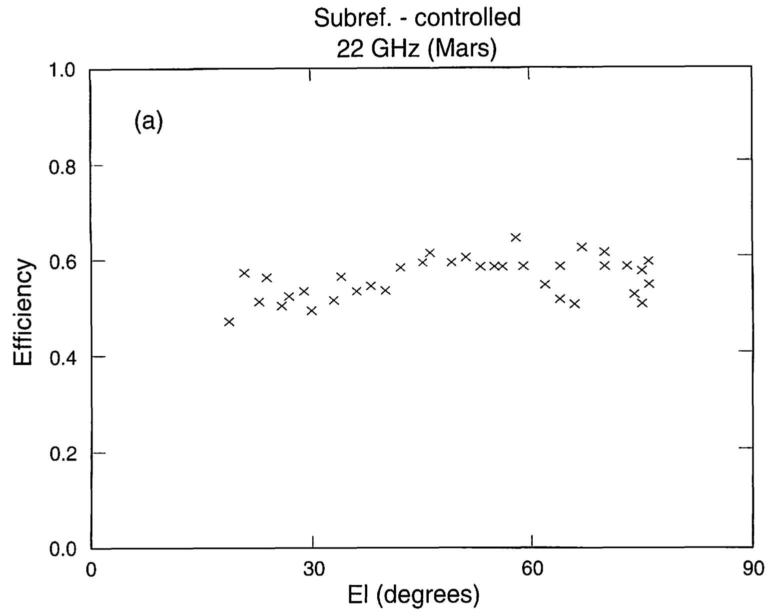
The Kashima 34 m antenna has an azimuth-elevation tracking system whose structure is illustrated in Fig. 4, and whose mechanical specifications are listed in Table 1. The tracking system used for the azimuth axis is the "rail tracking type," namely the main unit of the antenna system rotates on "the azimuth rail" to change the azimuth angle. Because one of the main study targets of this antenna is precise geodesy and the antenna is very heavy (about 400 tons), the basement of the azimuth rail is firmly connected to the hard ground by long piles, and consists of concrete blocks and iron blocks. The azimuth rail (called "wear-strips") has a thickness of about 3 cm and is made of hard steel fixed on the iron blocks by bolts. The wear-strips form a circle. If the surface of the wear-strips is damaged, it is only necessary to replace the wear-strips, and this can be easily performed. After the antenna was in operation for about 3 years, the surface of the wear-strips was damaged by rust and we exchanged them with new ones.

The main frame of the antenna is designed rigidly, and its driving system is also designed for the geodetic VLBI. That is, the geodetic purpose VLBI requires as many radio sources such as quasars as possible to be observed during 24 hours. The number of observations in a 24 hours experiment is more than 200. The azimuth and elevation driving speeds need therefore as fast as possible, and they are more than 0.7 degrees/sec, comparatively fast when compared with those of other large-aperture antennas.

This antenna also has the highly precise pointing accuracy, better than 7″, needed to perform the millimeter-wave observations. This positioning accuracy is performed by using the optical rotary encoders which have 20 bits of angular resolution.

2.2 Main Dish

The main dish of the 34 m antenna has a rigid structure and its surface was adjusted to be best at the elevation angle of 45 degrees, where its surface accuracy is about 0.17 mm (rms). Many factors



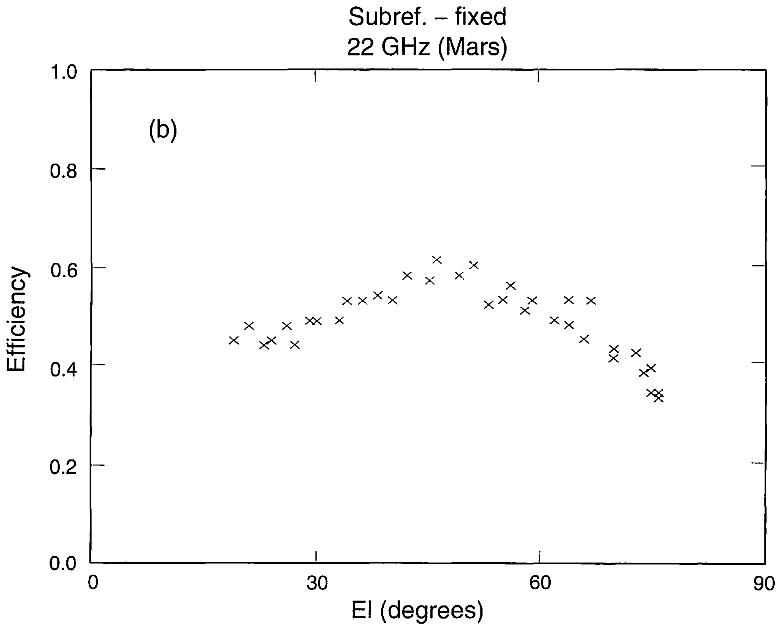


Fig. 6 Efficiency of the 34 m antenna at 22 GHz: (a) active subreflector control is on, (b) active subreflector control is off.

Table 2 Receivers specifications

Band	Frequency	Band width	T_{rec}	T_{sys}	Efficiency
1.5 GHz	1.35–1.75 GHz	400 MHz	10 K	38 K	68%
2 GHz	2.15–2.35 GHz	200 MHz	11 K	71 K	65%
5 GHz	4.60–5.10 GHz	500 MHz	25 K	60 K	71%
8 GHz[1]	8.18–8.60 GHz	420 MHz	8 K	48 K	56%
8 GHz[2]	8.18–8.60 GHz	420 MHz	12 K	53 K	56%
8 GHz[2]	7.86–8.36 GHz	500 MHz	13 K	56 K	58%
10 GHz	10.20–10.70 GHz	500 MHz	43 K	70 K	64%
15 GHz	14.40–14.90 GHz	600 MHz	42 K	106 K	51%
15 GHz	14.90–15.40 GHz	500 MHz	40 K	108 K	47%
22 GHz	21.88–22.38 GHz	500 MHz	101 K	189 K	58%
22 GHz	23.58–24.08 GHz	500 MHz	158 K	223 K	54%
43 GHz	42.80–43.30 GHz	500 MHz	400 K	1200 K	44%

T_{rec}: Receiver noise temperature
T_{sys}: System noise temperature at El = 90 degrees
1: 8 GHz receiver for normal receiving band
2: 8 GHz receiver for wide receiving band

such as gravitation, wind, and temperature, reduce the typical surface accuracy to about 0.3 mm (rms) during observations, but this value is still good enough for the millimeter-wave observations.

2.3 Subreflector

The beam optics of the antenna is a modified cassegrain type and its focal point is at "the feed corn" illustrated in Fig. 4. As it will described in a later section, it has a multireceiver system in the ETR (Elevation Tilt Room) to keep the focal point at the center of each receiver's feed horn (the subreflector is mechanically controlled to feed the received signal to the selected feed horn). Its structure is shown in Fig. 5. The subreflector can move along the X, Y, and Z axes and can rotate around the X and Y axes. This movement is accomplished by using five actuators, and their positioning accuracy is within 0.01 mm. The subreflector can be controlled to keep the maximum efficiency when the main dish shape is changed by the gravitational effect due to changes in elevation angle. This active subreflector control system is highly effective for observations at the higher frequencies, and Fig. 6(a) and 6(b) show results obtained with and without this control[(6)]. When the active subreflector control is in operation, the efficiency can be kept almost constant for elevation angle changes from 20 degrees to 80 degrees, whereas efficiency is reduced at low and high elevation angles when active subreflector control is not in operation.

2.4 Receivers System

Table 2 lists the specifications of the receivers mounted in the 34 m antenna. In addition to receivers listed in Table 2, 300 MHz and 600 MHz receivers were mounted on the front feed point of the main dish when the antenna was constructed. The radio conditions at these bands were so bad around Kashima Space Research Center, that these receivers were removed.

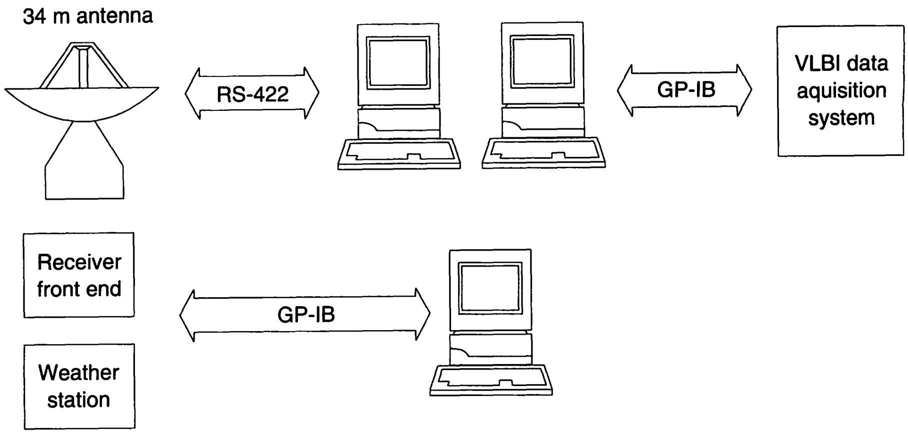


Fig. 7 Computer system for controlling the 34 m antenna

The receivers listed in Table 2 are cooled to 15 K by a closed-cycle gas helium system to reduce amplifier noise (each amplifier uses the High Electron Mobility Transistors). The receivers are separated into four groups;

Group 1; 1.5 GHz
Group 2; 2 GHz and 8 GHz
Group 3; 5 GHz and 10 GHz
Group 4; 15/22/43 GHz

Each group is mounted on a stage and when a receiver group is selected, it is moved by the trolley system to the focal point. The receiver groups can be exchanged from the experimental room by using the receiver control computer.

The receiver group 2, 2 GHz band and 8 GHz band, can receive signals simultaneously to perform the geodetic VLBI, and can provide ionospheric delay compensation. The other receivers cannot be used simultaneously, but the receivers can be exchanged within about 10 minutes.

Each receiver can select the receiving polarities, LHCP (Left Hand Circular Polarity) or RHCP (Right Hand Circular Polarization), of the receiving signal. This selection is also made from the experimental room by using a computer system.

2.5 Control System

The entire system of the 34 m antenna is controlled by small computers in the experimental room. In the VLBI experiments, three computer systems are used, one to control the antenna driving, the second one to control the receiver system, and the third one to control the VLBI equipment. Figure 7 shows the schematic diagram of the control system. The VLBI experiments are performed by using the operating software called "NKAOS," which was modified for the 34 m antenna from the KAOS (Kashima Automatically Observation System)[7] which was developed for the K-3 VLBI system.

3. Upgrading Efforts of the 34 m Antenna

3.1 Azimuth Wear-strip Cover

Because the Kashima Space Research Center is near the seaside, because the humidity and temperature in summer are high, and because of the operational form of the geodetic VLBI experiments, rust damaged the wear strips of the azimuth rail. After about three years operation the wear-strips were deeply rutted and made steps of about 1 mm at the joint points of the wear-strips. The wear-strips were therefore replaced in 1992, and to prevent further damage an azimuth rail cover was attached in 1993. The wear-strip is kept dry by the rail cover, which is expected to protect the wear-strip from rust and thereby ensure their long lifetime.

3.2 Optical-fiber IF Signal Transmission

When the 34 m antenna was constructed, coaxial cables were used as transmission lines for the intermediate frequency signal (IF signal) converted from the received band. These cables, too, were damaged by the humidity, especially at the junction points placed outside, and were therefore in 1992 replaced by high-performance optical-fiber cables. The resultant optical signal transmission system can transmit the wideband signal without amplitude equalizers whereas the coaxial cable needs, so it makes the transmission system for the IF signal very simple and is expected to improve the performance of the signal transmission.

3.3 New Millimeter-wave Receiving System

A 43 GHz receiver developed by Nobeyama Radio Observatory of NAO was mounted on the 34 m antenna by Nobeyama Radio Observatory in cooperation between CRL and NAO. It uses the HEMT-type low-noise amplifier but does not have a good noise temperature. The survey observation of SiO Masers and the 43 GHz VLBI experiments with the Nobeyama 45 m antenna were performed by using this 43 GHz receiver because the flux density of SiO masers are very high and the 34 m and 45 m antennas have very large apertures. But to perform more sensitive observations and for the VLBI experiment with smaller-aperture antennas, it is necessary to improve the receiver noise temperature. A new millimeter-wave receiver that uses the SIS (Superconductivity-Insulator-Superconductivity) mixer is therefore under development in a collaborative effort by CRL and NRO. This receiver is expected to greatly increase the sensitivity of the 40 GHz band receiving system of the 34 m antenna. A 100 GHz band SIS-type receiver system is also scheduled to be mounted on the 34 m antenna.

4. Observations Using the 34 m Antenna

The VLBI experiments using the Western Pacific VLBI Network system were performed from 1989 to 1993, and the details and results of these experiments are given in the papers in this special issue[(8)-(11)]. This antenna has also been used, for many purpose, as a main tool of the precise space and time measurement project. The main subjects of this project are:
1) precise earth rotation measurement experiments,
2) developments of next-generation precise VLBI facilities and equipment[(12)],
3) radio astronomical observations[(13)],

4) investigation of interstellar propagation scintillation (IPS) due to solar wind,
5) precise timing signal observation of the high stable millisecond pulsar for the precise time scale(14).

There are also many proposals from many other organizations who want to use the 34 m antenna in collaborations with CRL.

5. Conclusion

The Western Pacific VLBI Network experiments were successfully performed using the 34 m antenna as a main VLBI station and the results and experience gained in those experiments applied for the new CRL project (called "Key Stone Project") which will precisely measure crustal deformation around the Tokyo Metropolitan area.

The Kashima 34 m antenna is the first large antenna that was imported to Japan. It is a very powerful observation tool, but we should make efforts that this antenna will be as our own tool and as a tool at the forefront of science.

6. Acknowledgment

We would like to express our thanks to everyone who helped to construct the Kashima 34 m antenna.

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II. OVERVIEW OF THE EXPERIMENT SYSTEM

II.2 STATIONS IN THE REMOTE ISLANDS

By
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ABSTRACT

This paper describes the system used in two remote islands of the Western Pacific VLBI network. This network was established as a regional VLBI network dedicated to geodetic measurements. The main purpose of the network is to study the plate motion around Japan. Minamitorishima (Marcus) Island and Minamidaitoh Island were selected as respective sites to study the behavior of the Pacific and the Philippine Sea plates. The system is compact and reliable features that are required for construction, transportation and operation of the VLBI system in remote sites.

Keywords: VLBI (Very Long Baseline Interferometry), WPVN (Western Pacific VLBI network), the Pacific Plate, the Philippine Sea Plate, FSS (Frequency Selective Surface)

1. Introduction

The geodynamics of the Earth have been studied in the Crustal Dynamics Project (CDP) organized by NASA. This project employs a space geodetic global network. The Communications Research Laboratory (CRL) cooperated with NASA to conduct the CDP project by developing the Very Long Baseline Interferometry (VLBI) system and to perform experiments[1]. It is important to have a regional VLBI network in addition to a global network, so that independent observational activities may be enhanced in each part of the globe. As a regional Japanese VLBI network, the Western Pacific VLBI network (WPVN) was constructed to study the plate motion in this region. The network consists of a main station at Kashima, sub-stations at Minamitorishima Island and at Minamidaitoh Island, and a Shanghai station (Fig. 1). In the WPVN, CRL first deployed VLBI stations on remote islands. Shanghai is the only Chinese VLBI station in the WPVN. It is equipped with a 25 m antenna. These VLBI stations were deployed to examine behavior of plates around Japan. The Kashima station is located on the North American Plate. The Minamitorishima Island station is located on the Pacific Plate. The Minamidaitoh Island station is located on the Philippine Sea Plate. The Shanghai station is founded on the Eurasian plate. To establish the WPVN, the CRL

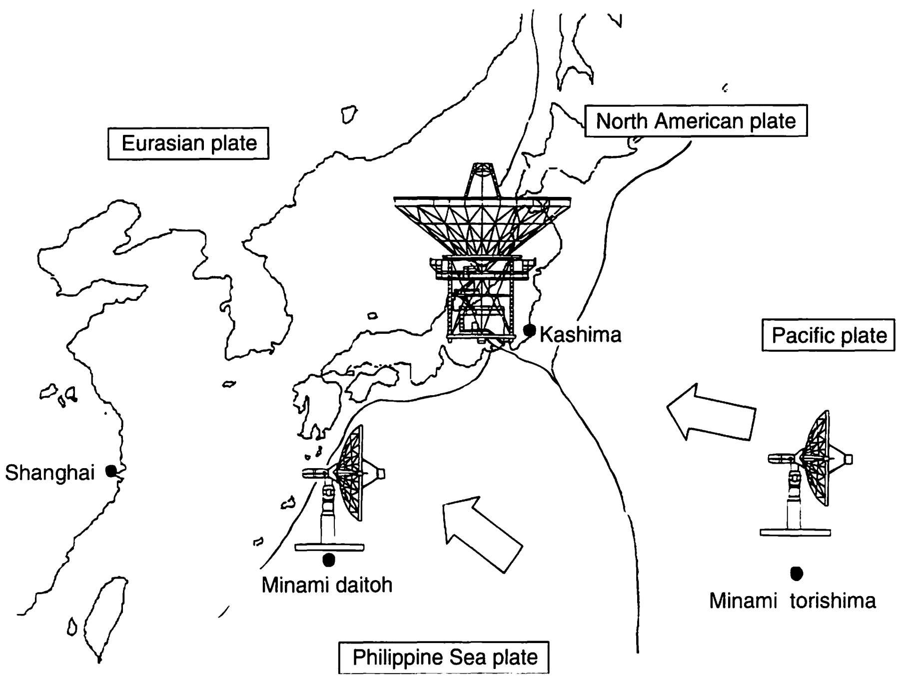

Fig. 1 The Western Pacific VLBI network

constructed new VLBI facilities at Kashima and the Minamitorishima stations. At the Kashima station, a 34 m antenna was constructed as a main station of WPVN (See II-1 in this issue). For the Minamidaitoh station, we utilized a mobile VLBI system with 3 m antenna.

We describe the two remote island stations and report on the performance of their observation systems in these pages. For the experiments that were performed, the VLBI system was transported to the remote islands. Since the newly developed K-4 system[2] is compact and reliable, it was used in the most WPVN experiments. Transportation and operation of the K-4 system was easier than the conventional K-3 system which was developed for the use in a fixed station. The planned term of the WPVN experiment was five years, beginning in 1989.

2. The VLBI Station in the Minamitorishima Island

If we were to study the motion of the Pacific plate using a Japanese island, Minamitorishima Island is the only possible candidate. Hence, this is a Hobson's choice; we have no real choice. However, the position of the island is, in fact, ideal for plate motion study. Since the island is located far from the plate boundary (almost 1,000 km from the closest boundary), motion on this station should clearly indicate Pacific plate behavior. While the Pacific plate is one of the largest on earth, the number of VLBI stations on this plate is small. If we exclude stations close to the plate boundaries, only Kauai and Kwajalein stations remain as suitable sites for the study of plate motion. The Kwajalein station, however, operates only on a temporary basis. Hence, only the Kauai station has been available to date. An additional station was needed. The Minamitorishima island is located on the eastern end of Japan. It is a coral island (Fig. 2). The island is so flat that sea wind blows through the island.

Fig. 2 Photograph of Minamitorishima Island

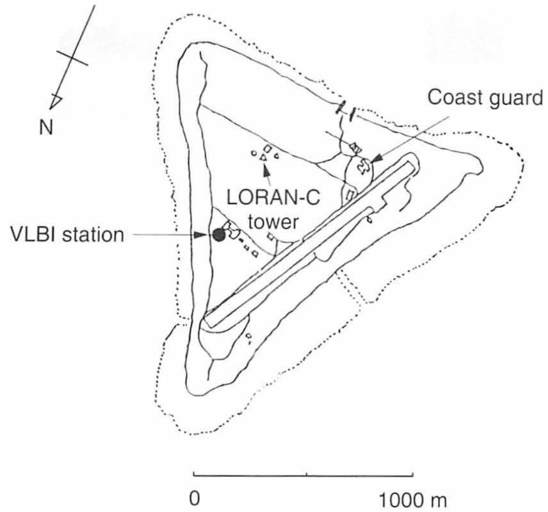

Fig. 3 Map of Minamitorishima Island

The island is owned by the Ministry of Finance and the Forestry Agency. Currently, only staff of the meteorological observatory and maritime self-defense agency are living there. The shape of the island is triangular, and the length of each side is about 1.5 km. Transportation to the island is only by airplane.

The observation system in the Minamitorishima Island consists of a 10 m antenna, a container, a power supply generator and an INMARSAT compact ground terminal for satellite communication. The container is equipped with an antenna control unit, a VLBI data acquisition terminal, a weather monitor terminal and a personal computer for system control. The 10 m antenna is located 100 m away from the coast. A map of the antenna site is provided in Fig. 3. Mechanical system corrosion and winds reaching 60 m/sec were anticipated, so the original design of the 10 m antenna by S/A (Scientific Atlanta) for satellite communications was modified to meet WPVN specification. The antenna was constructed in May, 1989 (Fig. 4).

It was anticipated that radio signal from the LORAN-C transmitter may interfere the weak signals from celestial radio sources for the VLBI experiments. Although the 100 kHz LORAN-C

Fig. 4 Photograph of the 10 m antenna

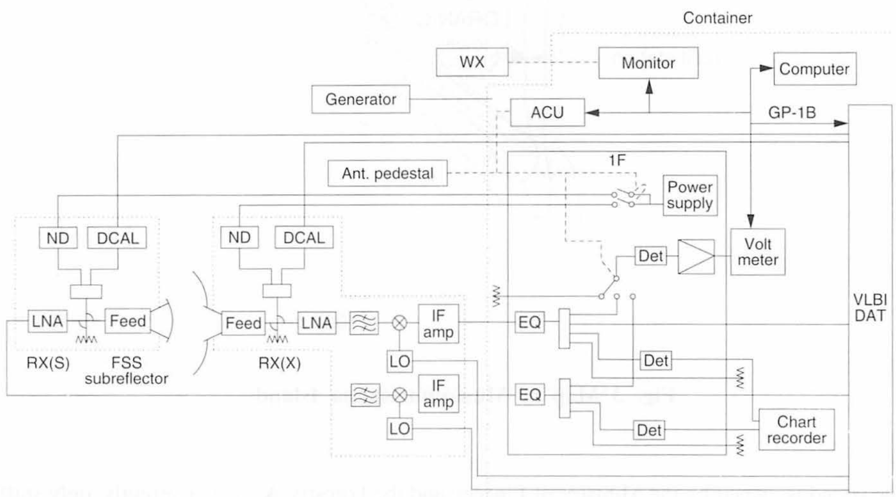

Fig. 5 Block diagram of the observation system of the Minamitorishima station

signal is transmitted at 1.2 MW from the 110 m tower on the island, spurious signal to interfere the VLBI was not detected by measurements.

A block diagram of the Minamitorishima station is depicted in Fig. 5. Performance of the 10 m antenna and receivers is shown in Table 1. As a geodetic VLBI station, both S and X band receiving systems were implemented. A Frequency Selective Surface (FSS) was mounted as a sub reflector for the 10 m antenna to enable frequency separation. The S band signal is fed through the sub reflector to the prime focus, while the X band signal is reflected at the sub reflector and then fed to the receiver at the Cassegrain focus. The antenna slew rate was 11 deg/sec and 5 deg/sec in El. A short slewing time to change radio sources during the VLBI experiment improves the precision of the baseline

Table 1 Performance of (a) the 10 m antenna and (b) receivers for the Minamitorishima Island

(a) a 10 m antenna		
Main reflector		10 m
Subreflector		0.8 m
Mount		Az-El
Polarization		RHCP
Surface accuracy		0.86 mm rms
Maximum drive speed		11 deg/sec (Az) 5 deg/sec (El)
Cable wrap		+360/−360 deg (Az) −2/+182 deg (El)
Wind velocity		Max. 25 m/sec (operable) Max. 60 m/sec (survival)
Weight		25 ton
(b) Receivers		
S band	2.20–2.32 GHz	100 K
X band	8.18–8.60 GHz	170 K

measurements. Electric power to drive antenna is provided by the 70 kVA generators. Source tracking and other automatic VLBI operations are made by an HP personal computer. As a stable frequency source, an oscillator composed of a Cs clock and a stable crystal oscillator (Cs-X'tal)[3] was used in most experiments.

CRL staff visited the island only during VLBI experiments and for maintenance. Damage of the 10 m antenna from severe environmental condition remains one of the biggest problems. In severe conditions, the G/T of the antenna at the island was lower than the value at Kashima. We believe salt adhesion is one cause.

3. The VLBI Station in the Minamidaitoh Island

The Great Kanto earthquake, which occurred in 1923 in the Tokyo Metropolitan area, was triggered by the motion of the Philippine Sea plate. The motion of this plate is not well understood from geological surveys because only information from past earthquakes is available[4]. Hence, observed results by modern techniques are important. With this plate, there are many possible VLBI antenna sites. Okinotorishima Island is at an ideal location from the plate boundary. It is, however, too small for a VLBI station. Minamidaitoh Island was selected as the site.

This island is located 392 km east of Okinawa. It is for 5.78 km east to west and 6.54 km from north to south (Fig. 6). At the highest point, the island is 75.8 m above sea level. The antenna position is also indicated in Fig. 6. Most of the island is used for agriculture. Access to the island is possible by a small airplane for operators and by a ship for transportation of experimental equipment.

The observation system at this island consists of a 3 m antenna, an X band receiver, a back end, a data recorder and a Cs-X'tal clock. Although an 11 m antenna was planned for the island after an experimental test using the 3 m antenna, financial constraints have prevented this. Hence, we have conducted our experiments with the 3 m antenna. A picture of this antenna is shown in Fig. 7. The

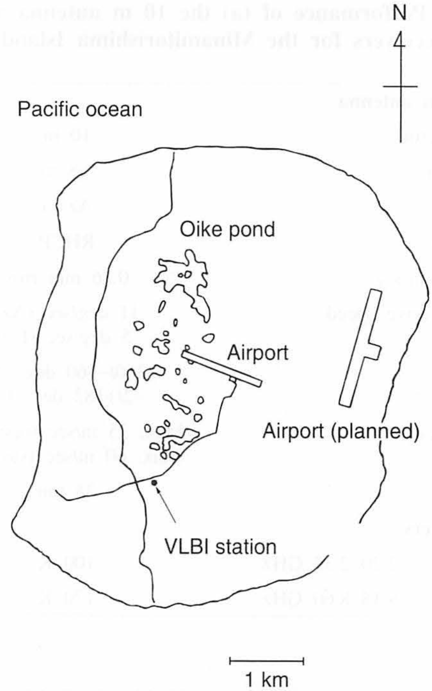

Fig. 6 Map of Minamidaitoh island

Fig. 7 Photograph of the 3 m antenna

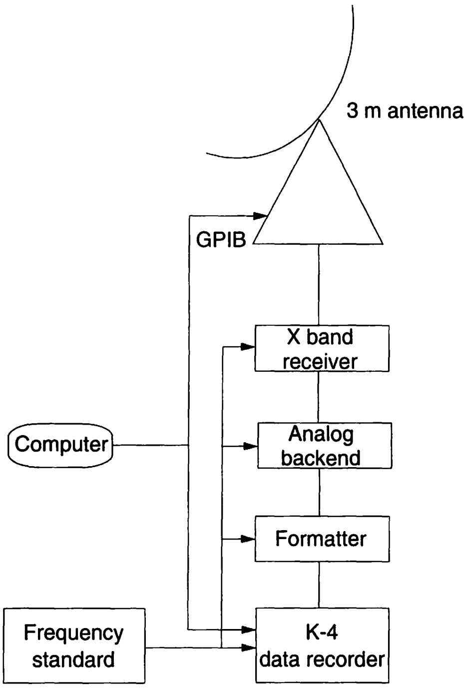

Fig. 8 Schematic diagram of the observation system of the Minamidaitoh station

Table 2 Performance of the 3 m antenna and receiver used at Minamidaitoh Island

3 m antenna and a receiver	
Main reflector	3 m
Mount	Az-El
Polarization	RHCP
Maximum drive speed	10 deg/sec (Az) 10 deg/sec (El)
Cable Wrap	+270/–270 deg (Az) –2/+182 deg (El)
Weight	1.4 ton
RX (Low)	7.86–8.28 GHz
RX (High)	8.18–8.60 GHz
System noise temperature	120 K

antenna system was originally developed for a mobile VLBI experiment. The antenna was also utilized for experiments at Koganei, Wakkanai and Okinawa. It was the smallest antenna for VLBI before development of the 2.4 m antenna[5]. Following the tests, the antenna was transported to the island. Since this system has only an X band receiving capability (Fig. 8), ionospheric correction was necessary to be made independently. Performance of this antenna and its receiver are shown in Table 2.

The signal-to-noise ratio of this system is lower than that in the system of the larger antenna. To overcome this problem, bandwidth synthesis with a wide band was made by high and low frequency band receivers in the X band. Automatic operation of the VLBI system is possible by personal computer.

4. Conclusions

The VLBI facilities, including their antennas, were deployed on the remote islands in the WPVN. These are compact and reliable systems. Antenna size on the remote islands is smaller because a large dish antenna (34 m) was constructed at Kashima as a main WPVN station. The K-4 VLBI data acquisition system was used in most experiments, because the weight of the K-4 back end system is 167 kg without a frequency standard. This is one third of the K-3 back end weight. Furthermore the K-4 system is also highly reliable and easy to use.

WPVN data has been obtained and analyzed. The results are reported in this issue and by Yoshino[6]. This data is provided to NASA to improve the global terrestrial reference frame.

5. Acknowledgments

We would like to thank all the staff who helped to establish and operate the WPVN network. We are thankful for the project support received on Minamitorishima Island from the Defense Agency and the Meteorological Agency. Our experiment at the Minamidaitoh Island was also largely supported by the Meteorological Agency.

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II. OVERVIEW OF THE EXPERIMENT SYSTEM

II.3 THE WESTERN PACIFIC GEODETIC PROJECT'S DATA ACQUISITION AND PROCESSING SYSTEM

By
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ABSTRACT

Research into crystal oscillators has made remarkable progress in recent years, and the stability of selected such oscillators can reach 3×10^{-13}, a value comparable with the stability of the atmosphere. Instead of a hydrogen maser, a carefully selected crystal oscillator phase locked to a cesium frequency standard for 100-second time ranges was adopted as the time and frequency standard of a geodetic Very Long Baseline Interferometry (VLBI) experiment. The VLBI system operated in Marcus island, had to be transportable, especially the reference clock and data acquisition systems. The K-4 system uses a rotary-head cassette recorder that makes the system smaller and easier to operate. The system is a compact VLBI terminal, one fourth the weight and one fifth the size of the Mark-III and K-3 systems. The K-4 system can be made fully output-data compatible with the Mark-III and the K-3 systems by using input- and output-interface units. The correlation processing was handled by K-3 correlation processor. VLBI experiments were carried out for four years (from 1988) using these systems at a baseline of 1000 km+. The position of Marcus island was successfully detected within 5 mm, and its site velocity within 5 mm/year.

Keywords: K-4, data acquisition terminal, correlation processor

1. Introduction

It is difficult to transport a hydrogen maser and a K-3/Mark-III terminal for a temporary VLBI experiment to a remote island such as Marcus island. The frequency standard used for VLBI must be stable both for long time ranges (more than 100 sec) and for short time ranges (less than 100 sec). Short time-range stability is essential for maintaining coherence, and long time-range stability is necessary for regulating the durations of observations. Since the stability of the atmosphere as measured by VLBI is approximately 10^{-13} ($\tau < 1000$ sec), atmospheric-phase scintillation degrades the coherence of VLBI data, which is independent of the phase fluctuation of the reference signal. Research into crystal oscillators has made remarkable progress in recent years, and the stability of

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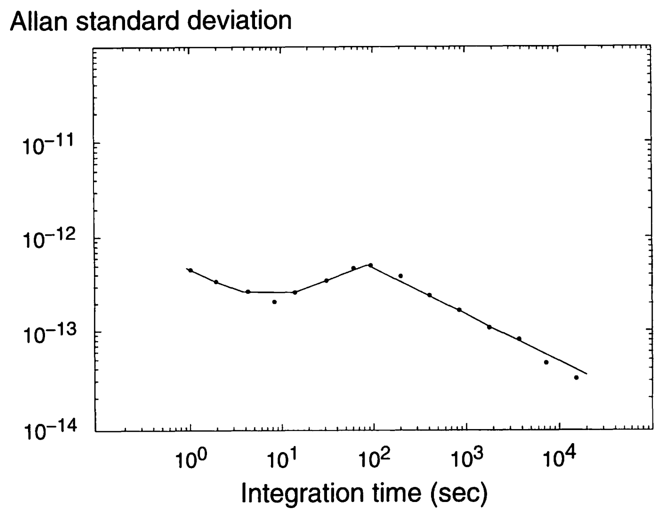

Fig. 1 Measured stability of the cesium-crystal system

selected crystal oscillators can reach $\sigma_y(\tau < 100 \text{ sec}) = 3 \times 10^{-13}$, which is comparable to the stability of the atmosphere. A new frequency system, which utilizes a selected crystal oscillator phase locked to a cesium frequency standard (a cesium-crystal system) was produced for time ranges of over 100 seconds, because the stability of the cesium frequency standard is better than that of the crystal oscillator over long time periods.

In general, the standard K-4 system is equivalent to the Mark-IIIa system, but we adopted a rotary-head cassette recorder in place of the stationary-head open reel recorder. This concept is conducive to high performance for error free recording and ease of operation in VLBI experiments. The standard K-4 system has become the main VLBI data acquisition tool for domestic VLBI experiments in Japan. Both the cesium-crystal system and the standard K-4 system, have been operated at remote Japanese islands in Antarctica. After a large quantity of data has been acquired on magnetic tape by a VLBI data acquisition terminal, it should be processed by a correlation processor. In our case, the processor used was a K-3.

2. The Cesium-Crystal System

The stability of the frequency standard used for short time periods is an important factor in maintaining the coherence of received signals in VLBI experiments. However, VLBI observations made from the ground always suffer from the effects of atmospheric scintillation, resulting in a loss of coherence. Therefore, the stability of the atmosphere determines the limit of the frequency standard for short time-range. The stability of the atmosphere was determined to be about 1×10^{-13} at 100 sec by VLBI. The stability of the hydrogen maser at 100 sec is 1×10^{-14}, which is sufficiently stable compared with the atmosphere, while recent technological progress has produced crystal oscillators with stabilities of 3×10^{-13} (BVA style AT-cut resonator[11]), which is almost the same as atmospheric scintillation.

In considering the potential use of the crystal oscillator as a frequency standard for short time-range VLBI, the coherence loss Lc due to the instability in the frequency standard for 100 sec

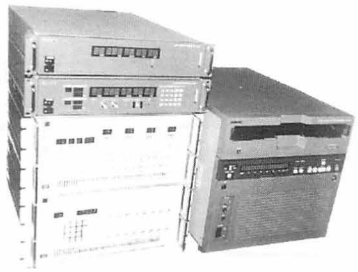

Fig. 2 The (standard) K-4 system

integration intervals can be estimated(2)(3). The calculated losses for the hydrogen maser and the crystal oscillator at integration intervals of 100 sec are 0.000123 and 0.041 respectively, which are small enough. However, long term stability of the frequency standard is necessary for regulating the results of each observation during analysis. Although the long term stability of the crystal oscillator is not acceptable for VLBI, the high performance cesium frequency standard has superior, and sufficient stability in the long term ($\sigma_y(\tau > 100) \leq 3 \times 10^{-13}$). If only the cesium frequency standard is used in VLBI experiments, however, it is impossible to maintain the coherence of the X band signal, as the stability of the cesium standard during short term signal integration is worse than $\sigma_y(1) = 10^{-12}$. Hence to satisfy the requirements of VLBI, a frequency standard is needed, which has the stability of the crystal oscillator for short time ranges and the stability of cesium for long time ranges. This can be created by using a crystal oscillator with its phase locked to a long time range cesium frequency standard. Figure 1 shows the measured stability of this cesium-crystal system. Results show that the crystal oscillator has good short-term stability but is inferior to the cesium frequency standard in the long term, while a cesium standard has excellent long-term stability but it is unusable for X band VLBI experiments. Therefore it can be seen that the combined cesium-crystal system meeting both requirements is better.

The optimum integration time depends on the stability of the crystal oscillator ($\sigma_y(1) = 4 \times 10^{-13}$) and that of the cesium frequency standard ($\sigma_y(1) = 3 \times 10^{-12}$). When using high performance commercial cesium, {SNR * coherence} reaches a maximum at about a 120-sec integration time. Since at that point the clock error is less than 0.05 nsec, it can be said that the optimum integration time for the system is 120 sec.

3. The K-4 Data-Acquisition System and Correlation Processing

The K-4 system consists of the following: (1) local oscillator, (2) video converter, (3) input-interface, (4) output-interface, (5) data recorder. This standard K-4 system (Fig. 2) is the first generation K-4 system. These systems use rotary-head cassette recorders that make them system smaller and easier to operate. At CRL, we are developing a new K-4 system multi-bit sampling, digital filter, and high-speed sampling capabilities. In this report we introduce only the first generation K-4 system. The standard K-4 system is a compact VLBI terminal, one fourth the weight and one fifth the size of the Mark-III and K-3 systems. The standard K-4 system can be made fully output-data compatible with the Mark-III and the K-3 systems by using input- and output-interface units. These units are compact and compatible with the Mark-III system. A block diagram of the data acquisition system is shown in Figure 3. The local oscillator synthesizes the local frequency signal for the video converter. The video converter converts one window in the intermediate frequency (IF)

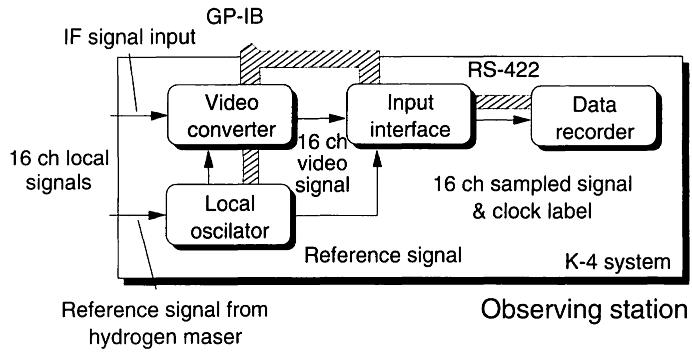

Fig. 3 The data acquisition site

signal (100–500 MHz) input into a video signal (0–2 or 4 MHz). The frequency conversion is achieved by an image rejection mixer using single sideband conversion. These blocks are the equivalents of the IF distributor, video converters (16 channels) and reference distributor of the Mark-III system.

The input-interface unit is used for data acquisition and recording at the VLBI observing station. It samples the video signal from the video converter, and sends the digital data to the data recorder together with the time data, which is derived from the external time standard signal. The output-interface unit is used at the correlation processing site. It converts the reproduced data into the appropriate output format, and sends it to the correlator. A format compatible with the Mark-III format is provided. Furthermore, another format which provides only digitized raw data signals, is provided for KSP correlator system (under development). When multi-baseline correlation processing is conducted, all the output-interface units are automatically synchronized with the main output-interface unit.

The two interface units mentioned make it possible to interface with current VLBI systems.

3.1 The Video Converter & The Local Oscillator

The local oscillator synthesizes the local frequency signal (500–1000 MHz in 10 kHz steps) for the video converter. The measured phase noise, which is calculated according to the measured Allan variance, is better than 3 deg. Coherence loss caused by this phase instability is less than 0.04%. The video converter and local oscillator are in commercial use as the first generation of the K-4 analog circuitry. The video converter converts windows in the IF signal input (100–500 MHz) into video signals (0–2 or 4 MHz). The frequency conversion is conducted by a single side-band image rejection mixer.

3.2 The Input-interface Unit

The input-interface unit samples the 16-channel (max.) video signal, and sends the sampled data to the data recorder proceeded by a time-data block. This format is quite different from that of the Mark-III. It was designed to make the best use of the K-4's recorder's abilities.

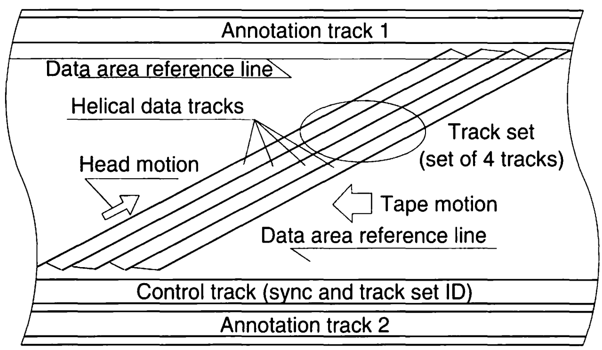

Fig. 4 Tape format and data format

3.3 The Data Recorder

A rotary-head recorer using a cassette tape (American National Standard 19 mm Type ID-1 Instrumentation Digital Cassette Format) was adopted. It is possible to read error rates from the data recorder whilst recording and replaying through the host computer. Helical scan recording is used to record digital signals at a high rate. With an L-size cassette, the K-4 recorder can provide up to 770 Gbits of data storage capacity at a recording rate of 64 Mbit/sec with a maximum recording time of 200 minutes (L-size cassette, 16 μm). Recording and playback are possible at different rates: 256, 128, 64, 32, 16 (Mbps), making the recorder suitable for many different applications. Superior Reed-Solomon error correction is performed by using custom encoder and decoder chips. The playback heads are located so that the recorded data can be played back immediately. This read-after-write facility makes it possible to monitor recording errors in real time. After correction, a bit error rate of less than 1×10^{-10} is achieved. The unit employs a built-in diagnostic system, designed to detect operation errors or hardware faults. Any error message or warning is fed into the host computer via the remote control interface, and from there to the front-panel display.

3.4 The Correlation Processing System

The K-4 recorder has helical data tracks, two longitudinal annotation tracks and a control track (Fig. 4). The track-set ID numbers are recorded on the control track, and can be read at any tape speed even during fast forward or rewind. The output-interface unit can control the synchronous replay of several data recorders, convert the track-set ID's for the data clock, and send the data to a correlator.

In multi-baseline correlation processing (Fig. 5), all of the output-interface units are daisy-chain connected via General Purpose Interface Bus (GPIB) and a timing control line. Therefore, the tape position data and the status data of all of the recorders can be exchanged via the output-interface units. The data played-back by the data recorder is written into a memory buffer. The main replay system (the main output-interface unit and the data recorder) and the sub-replay systems (the sub output-interface units and data recorders) can be synchronized in one-bit steps. The delay adjustment handled by controlling the buffer-memory (4 Mbits) and subsequent programmable shift registers (PSR). The signal (raw data) is unformatted instead of in Mark-III format.

The phase-difference measured between the playback and the external signals sent from the main replay system is monitored by the clock. The data measured is then sent to the main replay

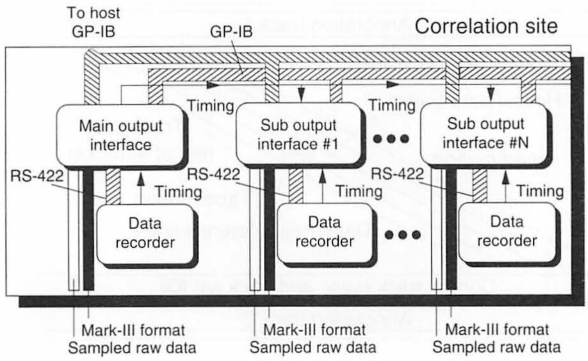

Fig. 5 The data processing site

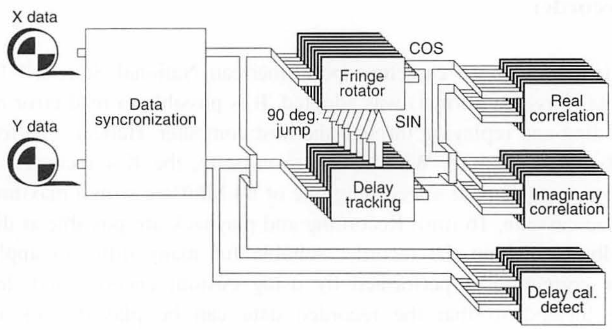

Fig. 6 The correlation processor

system, and used for bit synchronization (fine synchronization) between the main and sub-replay systems.

The cross correlation is carried out with an XF type K-3 VLBI correlation processor (Fig. 6), completed in 1984, which was designed to interface with the K-3/Mark-III data recorder. The K-4 output-interface is designed to be compatible with the K-3 Mark-III data recorder, and the output-interface unit has automatically data synchronization capability.

4. The Marcus Experiment

Experiments between Kashima and Marcus islands, (the most south-easterly points in Japan), were carried out once a year for four years as part of the Western Pacific Geodetic Project. At the Marcus island station, a 10 m diameter S/X dual band receiver was constructed. Since Marcus island is an isolated coral-reef island in the Pacific ocean, the station was not permanently manned all the VLBI observation equipment, including the frequency standard system and the data-recording system, were transported to the site each year from CRL. The VLBI system, which consists of the K-4 VLBI sub-system and the cesium-crystal sub-system, is quite compact and therefore has many advantages in operations such as this experiment where mobility is important. The present system is

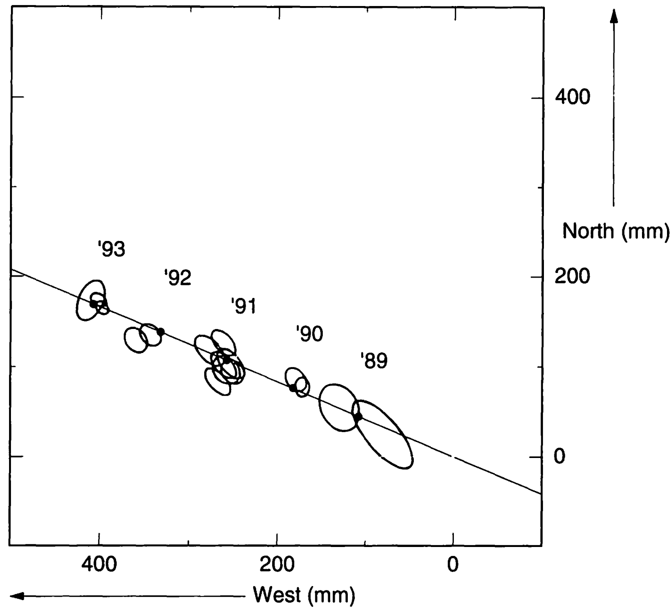

Fig. 7 Estimated positions and their 1 σ margins of error of the Marcus station are shown on the horizontal plane. (The cesium-crystal system was used as a reference signal from 1989 to 1992, and a hydrogen maser was used in 1993).

the smallest VLBI data acquisition system in the world. The K-4 is a data acquisition system which developed at CRL for transportable VLBI station applications. The frequency stability of the integrated frequency standard system is poorer than that normally found in a hydrogen maser, but provided a properly designed observation schedule is used, the overall results of geodetic VLBI measurements are comparable to those obtained during conventional experiments. To compensate for the poor frequency stability, only strong radio sources were selected and the recording time for each observation was restricted to 150 seconds (typical integration time is 120 seconds), thereby increasing the total number of observations.

Good fringes were obtained using this system. The baseline lengths at the epoch (1991.1.1), and their rates of change were estimated by a linear fit by applying least square residual method to the data. The results of the estimated rates were then compared with the expected values provided by the plate-motion model. The baseline length was determined within 5 mm and the site velocity was determined within 5 mm/year. These results are shown in Fig. 7. The excessive baseline measurements of Marcus may represent the west ward motion of the Marcus station with respect to the inner area of the Pacific Plate. The Marcus station was shut down after the last experiments in 1993.

We transported a hydrogen maser (CH1-75: made in Russia) to Marcus island in 1992 and in 1993. In 1992, the hydrogen maser did not work due to problems with the air conditioner, but we managed to carry out the experiments using the cesium-crystal system. In 1993, the experiments were carried out using the hydrogen maser, and the results were consistent with those using the cesium-crystal system for the previous three years. The results show the effectiveness of using a cesium-crystal system as the VLBI frequency standard (even for VLBI experiments with baselines of over 1000 km).

5. Summary and Conclusion

In the Western Pacific Geodetic Project, on Marcus island, an isolated coral reef island in the Pacific ocean, all VLBI observation equipment, including the frequency standard system and the data recording system, were transported to the site from CRL each year. The VLBI system used which consists of the K-4 VLBI sub-system and the cesium-crystal sub-system, is quite compact, and therefore has many advantages in experiments like this, where mobility is important. This system is the smallest VLBI data acquisition system in the worlds, and was also accurate enough to allow us to detect the position of Marcus island within 5 mm and its site velocity within 5 mm/year.

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II. OVERVIEW OF THE EXPERIMENT SYSTEM

II.4 DATA PROCESSING SOFTWARE AND DATA ANALYSIS SOFTWARE

By
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ABSTRACT

We developed the data processing and analysis software systems for the Western Pacific VLBI network project, and we introduce the software systems in this paper. A new computer system was introduced for the Western Pacific VLBI network project. As the processing system uses the new K-4 recorder, and we accommodate the processing software to the K-4 recorder using new computer HP9000-330. This is the first data processing system available for the K-4 recorder. In the data analysis, we use Mark-III software package developed by NASA (USA), such as the software for the Mark-III data base, the software for the calculated delay and the parameters estimation software. We present an overview of the software system. We also developed the software to set up the data into the Mark-III data base for the new computer system.

Keywords: VLBI, software, analysis, data processing, K-4

1. Introduction

The "Mark-III" VLBI system including the data processing software and data analysis software has been used worldwide for the geodetic VLBI experiments since 1975[1][2]. The Communications Research Laboratory (CRL) has participated in the international and domestic VLBI experiments since 1984. As the basis of the Mark-III system, we had developed our own software system (K-3 software system) which is compatible with the Mark-III system. For the data processing system, we developed the two types of software; the correlation processing software (KROSS)[3][4] compatible with the software "COREL" in the Mark-III system[1], and the bandwidth synthesis software "KOMB"[4][5] compatible with the Mark-III software "FRNGE." We also developed the four types of software for the data analysis; the software for the data base handler (KASTL) using the HP data base handler (IMAGE1000)[4][6], the software to set up the data into data base (KASET)[4][7], the software to get the calculated delay and delay rate (KAPRI)[4][8]-[10] which corresponds to the software "CALC"[2] in the Mark-III system, and the software to estimate the parameters (KLEAR)[4][11] which corresponds to the software "SOLVE"[2] in the Mark-III system. The K-3 software system was developed using an HP1000-45F computer system.

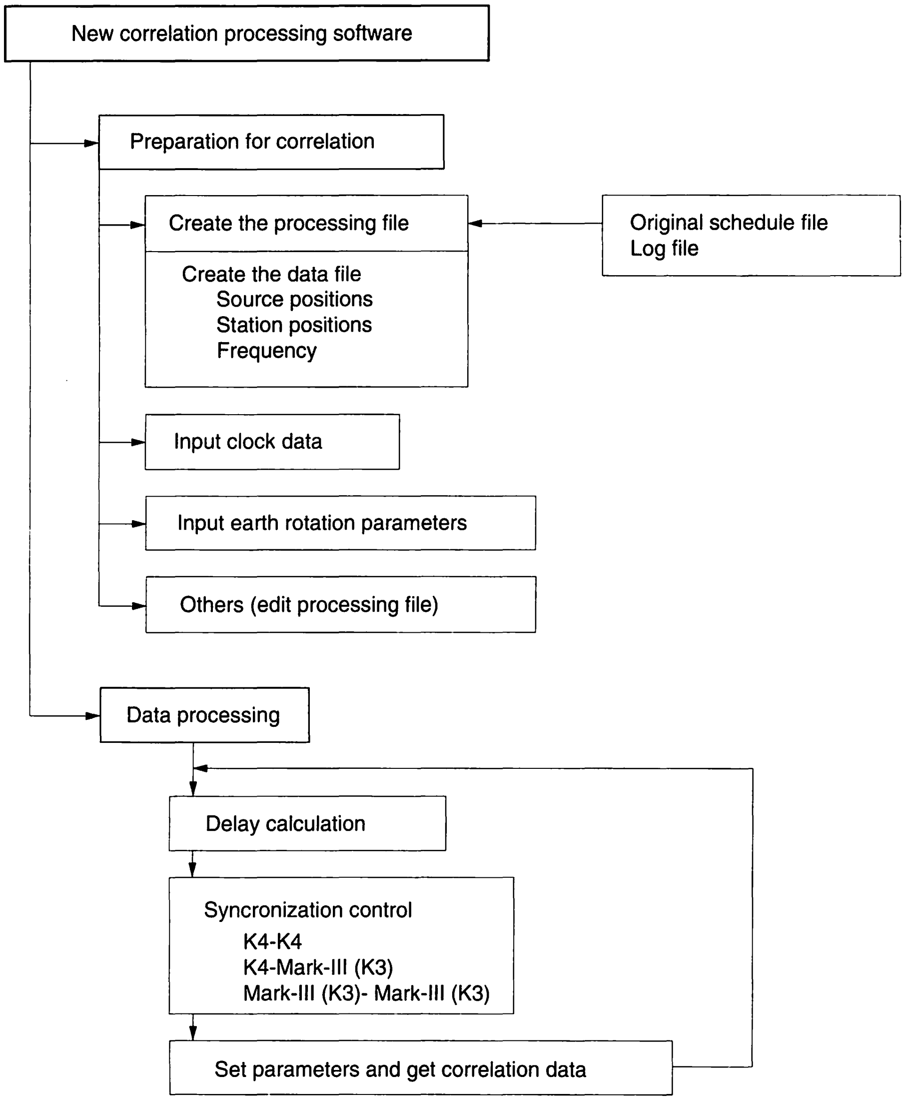

Fig. 1 The outline of the new correlation software

The Marcus and Daito stations in the Western Pacific VLBI network project are located on the island in the Pacific Ocean, and therefore the VLBI acquisition system had to be transportable. We developed the new VLBI system which uses the compact K-4 recorder[12]. We call it "K-4" system. In the Western Pacific VLBI network project, the new computer systems (HP1000 A900 and HP9000 330) which are three times faster than the previous systems were introduced for the data processing and data analysis. We developed the new data processing system for the K-4 recording system and the analysis system for the new computer system[4].

The Mark-III data analysis software used in the HP1000 A900 computer are also developed by NASA. For the compatibility, we adopted the Mark-III data analysis software, such as the software for the data base handler, the software (CALC) for the calculated delay and delay rate, and the parameter estimation software (SOLVE). Thus, they are easy to install in the computer system and they are compatible with the worldwide data base used in geodetic VLBI.

However, we had developed our own software to set up the data into the Mark-III data base. We conducted some of the experiments in the Western Pacific VLBI network project together with the stations in the Crustal Dynamics Project (CDP), such as Kauai (Hawaii), Gilmore-Creek (Alaska). In this case we had to send a Mark-III (K-3) tape which we copied from a K-4 tape recorded at Marcus. We developed the data converting software, which will be described later in this paper.

2. Data Processing Software

CRL developed a new recording system and called it the K-4 recording system[12]. New correlation processing software was also developed for this K-4 recording system.

The correlation processing software must control both the recorders and correlation processor. We developed the processing software using BASIC language using HP9000-330 personal computer since it can control the commands of GP-IB sequentially and it is especially easy to check and modify.

Bandwidth synthesis software runs in the HP1000-A900 minicomputer. Correlation data is transferred from the HP9000-330 computer for correlation processing, to the HP1000-A900 computer.

Figure 1 shows an outline of the new correlation processing software. Some files in the software are created in order to manage the correlation processing. These files are automatically created using only the original schedule file for individual experiments.

In the correlation processing, the data of a remote station is adjusted to the data of the reference station. This time adjustment is made using the calculated delay and delay rate for every parameter period (PP) of a few seconds, and the correlation data is integrated. Their calculated delay and delay rate for every PP are obtained using the 0th deviation (τ), the 1st deviation ($\dot{\tau}$), the 2nd deviation ($\ddot{\tau}$) and the 3 order derivation ($\dddot{\tau}$) with respect to time. In the old software, these values are the coefficients of Taylor expansion at the center of the observation. The difference between the calculated delay and the true delay is larger at the beginning and end of each observation in according to be far from the center of the observation. In this software, the 0th, 1st, 2nd, 3rd deviations are obtained using the approximation of the four order polynomial formulation. The entire duration of each observation is divided into 4 parts ($T_0 - 2\Delta T \sim T_0 - \Delta T$, $T_0 - \Delta T \sim T_0$, $T_0 \sim T_0 + \Delta T$, $T_0 + \Delta T \sim T_0 + 2\Delta T$ while $4\Delta T$ is the complete duration, and T_0 is the center of the observation and it is reference time of the observation). The values of 0th, 1st, 2nd, 3rd order deviations are calculated for the least square fittings as follows;

$$\begin{aligned}
\tau &= \tau_0 + \frac{\left(12(\tau_2 + \tau_3 - 2\tau_0) - 3(\tau_1 + \tau_4 - 2\tau_0)\right)}{35} \\
\dot{\tau} &= \frac{\left(\tau_1 - \tau_4 - 8(\tau_2 - \tau_3)\right)}{12\Delta T} \\
\ddot{\tau} &= \frac{\left(2(\tau_1 - \tau_0) - (\tau_2 - \tau_4) - (\tau_3 - \tau_4)\right)}{7(\Delta T)^2} \\
\dddot{\tau} &= \frac{\left(2(\tau_2 - \tau_3) + (\tau_4 - \tau_1)\right)}{2(\Delta T)^3}
\end{aligned} \qquad \text{(1)}$$

where τ_1, τ_2, τ_0, τ_3, τ_4 are the delays at $T_0 - 2\Delta T$, $T_0 - \Delta T$, T_0, $T_0 + \Delta T$, $T_0 + 2\Delta T$ for each observation.

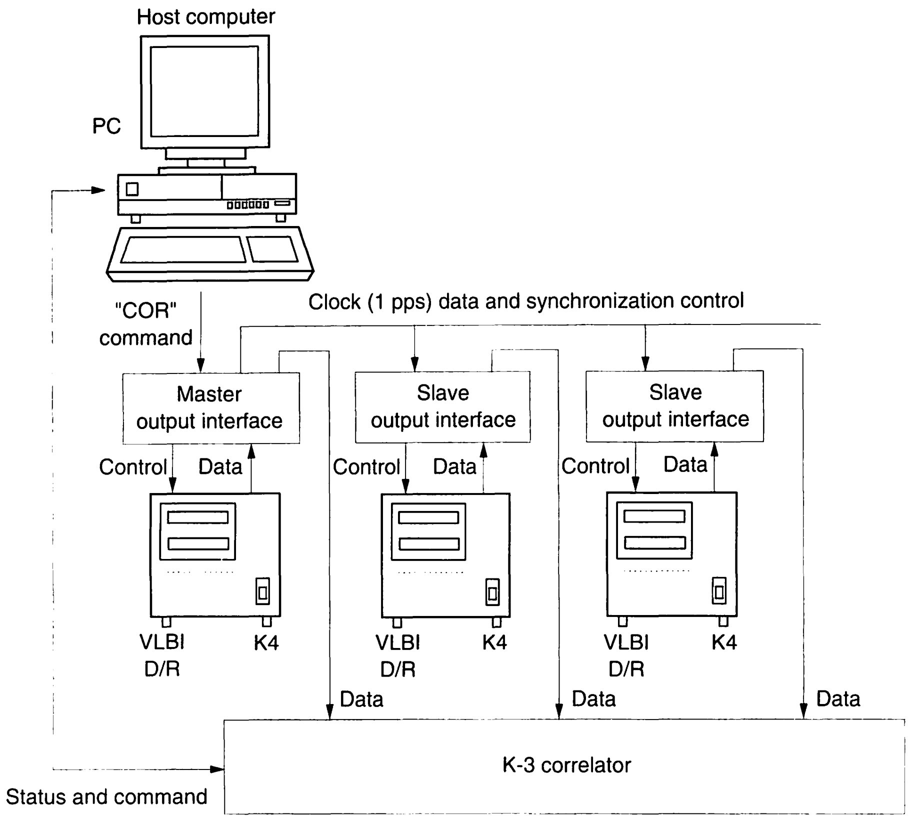

Fig. 2 The correlation processing among K4 recorders

The parts of each physical model used in the correlation processing software are separated into subroutines similar to KAPRI. The software structure is arranged to use the rotation matrices of precession, nutation, diurnal rotation and wobble. Atmospheric delay is calculated by using the fixed zenith path delay and the elevation mapping function. Some stations are located in elevated regions which are over 1000 m above sea level, and the zenith path delay varies by about 100 mb (10%). Then, we corrected for height in the zenith path delay.

This software can facilitate data processing both among K-3 (Mark-III) recorders, and among the new K-4 recorders, and also the correlation between K-3 recorders and K-4 recorders. In correlations between the K-3 and K-4 recorders, the K-4 recorder serves as the master for synchronization and it is not controlled. This control of the synchronization is the same as the control among the conventional K-3 systems. One command "COR" in the recording system is used to automatically synchronize K-4 system with other K-4 systems. Before fine automatic adjustment, rough tape synchronization to within 1 sec is achieved by using the position search command "PRL." Figures 2 and 3 show the correlation processing for each system combination.

The bandwidth synthesis software developed in the HP1000-45F computer system[4][5], was modified for the new computer system (HP1000 A900).

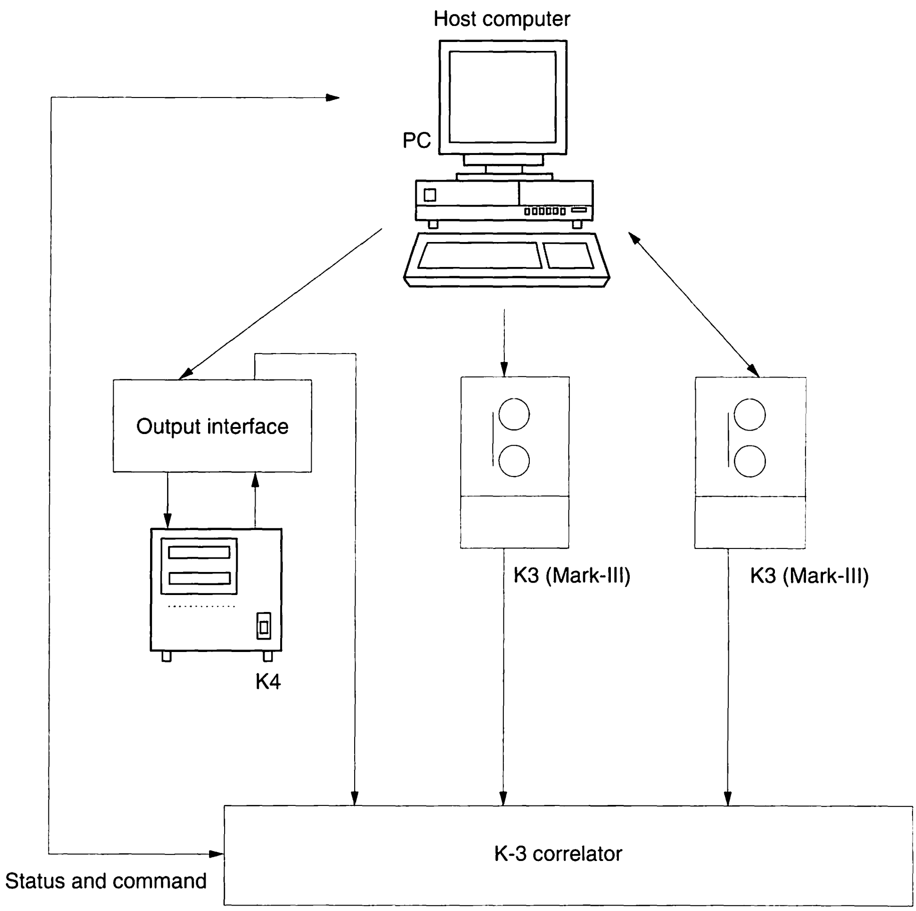

Fig. 3 The correlation processing between K4 recorder and Mark-III recorder

3. Analysis System

The analysis system consists of the data base handler, the software for the calculated delay, the parameter estimation software, and the setup software into the data base. Figure 4 shows the outline of the analysis system together with the data processing software.

3.1 Mark-III Data Base

The Mark-III data base[2][6] was invented in the geodetic VLBI group of CDP. This data base is used for the exchange of VLBI data in general, and our new system uses this system, too.

The Mark-III data base consists of a single file. The data is sequentially read from the data base in the analysis, and a lot of data base must be transferred. The single file Mark-III data base is convenient. The access speed is also fast.

The data is classified as two type. One is the common data in an experiment, such as the earth rotation parameters, station positions and source positions. The other is the observation data and

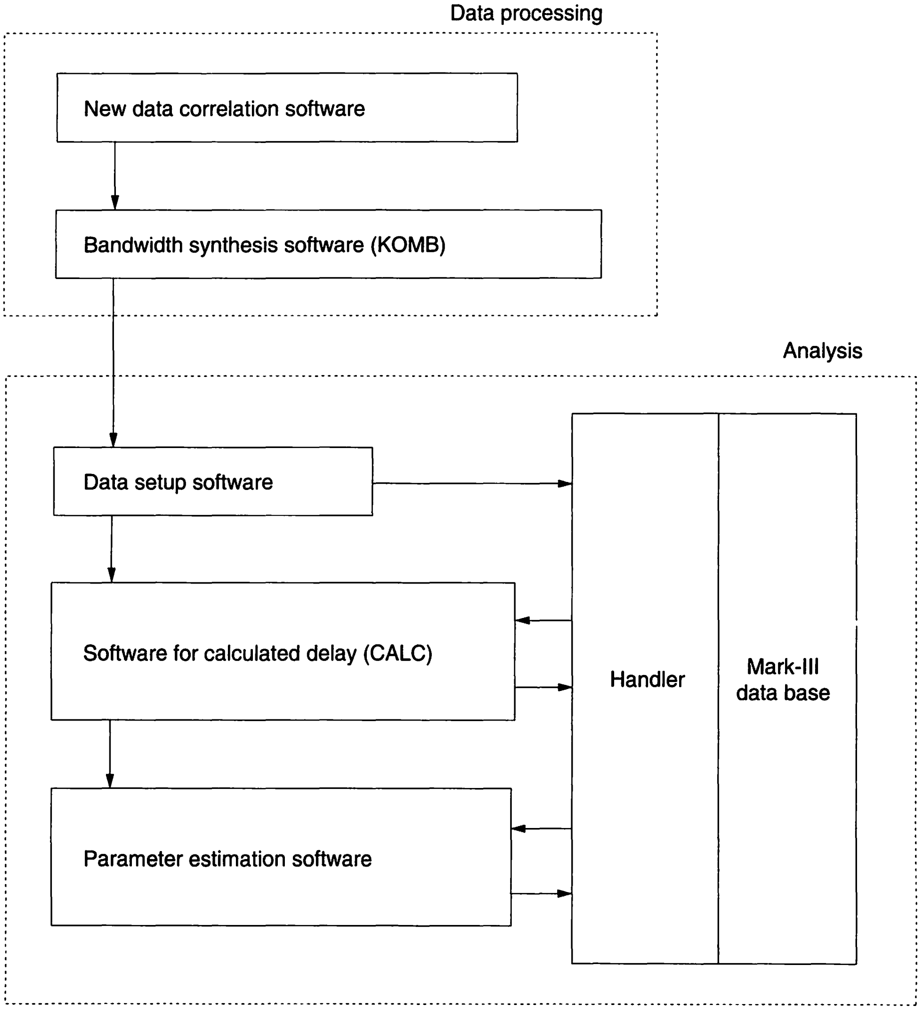

Fig. 4 The outline of the data processing and analysis software

calculated values of each occurrence. The occurrence is defined as each baseline in each observation. The data in the data base is divided into TOC (Table of Contents) 1, TOC2 and TOC3. The data of TOC1 is the common data in the experiment. The data of TOC2 and TOC3 are produced for every occurrence. The TOC2 data is mainly used for the baseline analysis, and the TOC3 data consists of the other correlation data.

The file of the data base consists of the header, the history, the definition of each data such as the array information and items, the data of TOC1, and the repeating data of TOC2 and TOC3. The file structure of the data base is shown in Table 1.

The data can be read from the data base and written in the data base using the data base handler. Figure 5 shows the method used by the program to read the data. First, the data base is opened by "KAI." The record pointer is moved by "MVREC," and the data is obtained by "GET." Finally the data base is closed by "FINIS."

Table 1 The file structure of Mark-III data base

Header of the data base File name, start date, experiment name, version	
History	HS .... ZZ
TOC1 item	TC, 1 TE, 1, n1, n2, n3, N1, N2, N3, n4, n5, N4, N5 8 character items, version, array × data number 32 character explanation × data number n1–n5: last number of 6 byte real, integer, ascii, 8 byte real, 2 byte integer N1–N5: number of 6 byte real, integer, ascii, 8 byte real, 2 byte integer
TOC2 item	TC, 2 TE, 1, n1, n2, n3, N1, N2, N3, n4, n5, N4, N5 8 character items, version, array × data number 32 character explanation × data number
TOC3 item	TC, 3 TE, 1, n1, n2, n3, N1, N2, N3, n4, n5, N4, N5 8 character items, version, array × data number
TOC1 data	Dr, 1 DE, 1, ... R 8 D (6 byte real data) × n1 +G (Integer data) × n2 11 (Ascii data) × n3 Q B. 8 D (8 byte real data) × n4 B: 5G (2 byte real data) × n5 ZZ
repeating	
TOC2 data	Dr, 2 DE, 1, ... R 8 D (6 byte real data) × n1 +G (Integer data) × n2 11 (Ascii data) × n3 Q B. 8 D (8 byte real data) × n4 B: 5G (2 byte real data) × n5 ZZ
TOC3 data	Dr, 3 DE, 1, ... R 8 D (6 byte real data) × n1 +G (Integer data) × n2 11 (Ascii data) × n3 Q B. 8 D (8 byte real data) × n4 B: 5G (2 byte real data) × n5 ZZ

3.2 Software for the Calculated Delay (CALC)

The data analysis is made to estimate the parameters using the observation delays and delay rates. We use the least square method to estimate the parameters, such as the baseline vector, clock parameters, atmospheric delay parameters, earth rotation parameters and source positions. In this

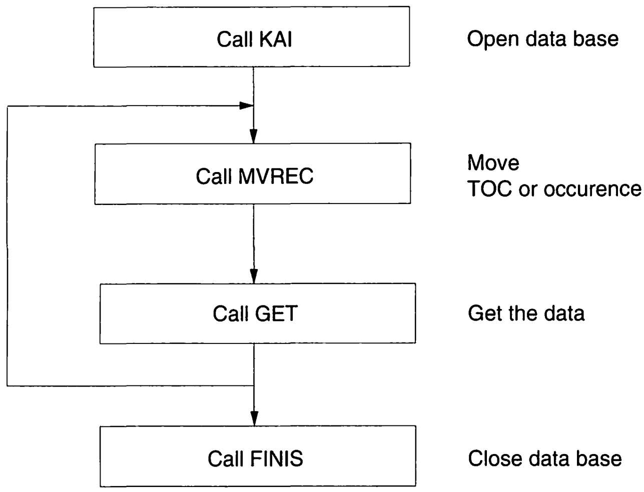

Fig. 5 The method in the program to read the data

case, precise calculated delay and delay rate are necessary. The calculated delay is required within an accuracy of less than 0.1 ns for the estimation within the precision of 0.1 ns. Many physical models and many calculations are needed to establish the calculated values. The partial differential of each parameter is also used to estimate the parameters. We repeatedly make a baseline analysis using the calculated delays and their differentials with regard to some parameters. It is effective for the calculated delays and their differentials to be sored in the data base.

Geometric delay is calculated using the baseline vector, the unit vector of source direction, and the rotation matrix which means the coordinate transformation due to precession, nutation, the diurnal earth rotation and the direction of the earth rotation and the rotation of the earth. The geometric delay is the delay within the solar system, and it should be transferred to the delay on the earth. This transformation represents the relativistic effects corresponding to the aberration and the movement of the stations during the delay. After the correction, the atmospheric delay is added to the calculated delay. We adopt CALC developed by GSFC (Goddard Space Flight Center)/NASA for the calculated delay. The physical models adopted will be presented in another paper in detail[2][8]-[10].

3.3 Parameter Estimation Software (SOLVE)

The "SOLVE" software makes an analysis by using observation data (O) and the calculated delays (C) using the least square method[4][11]. The estimated parameters are obtained so that $S = \sum_{i=1}^{N} [(O_i - C_i - \Delta C_i)^2/\sigma_i^2]/\sum_{i=1}^{N}(1/\sigma_i^2)$ becomes the minimum, where S is a weighted root mean square of the residuals, ΔC_i represents the correction based on the estimated parameters and σ_i is the error of each data. The estimated parameters can easily be selected from the computer display. The available estimated parameters are mainly clock offset and rate, atmospheric zenith path delay, station positions (X, Y, Z), earth rotation parameters, source positions and nutation. The clock parameters and atmospheric delay are estimated between epochs that are selected at the discretion of the analyst.

Initially, the ambiguity caused by the bandwidth synthesis should be eliminated from the observation delay. Next, data of poor or dubious quality are marked, and then the parameters and errors are estimated to minimize the value of S. The residual of $(O_i - C_i - \Delta C_i)$ is plotted, and an

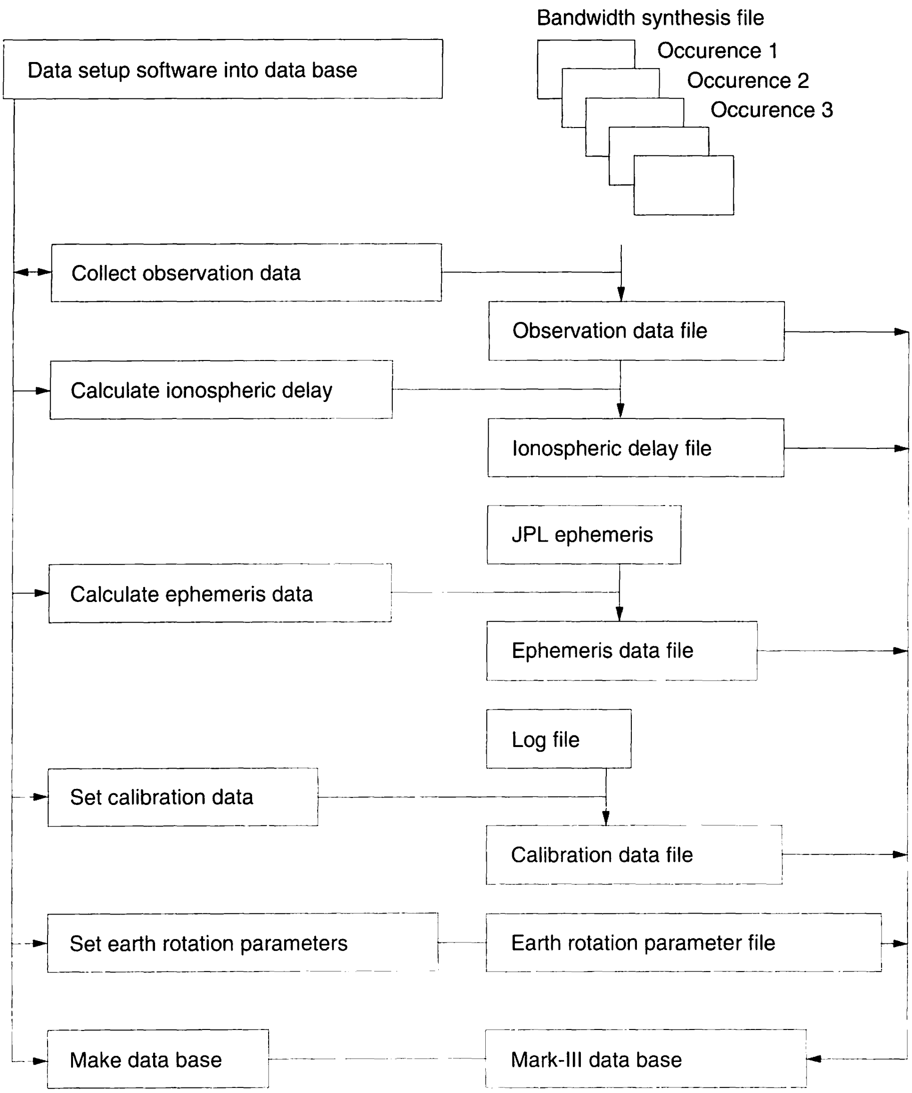

Fig. 6 The algorithm of the data setup software

assessment is made whether any systematic error exists. When the residual becomes the random distribution, the analysis is complete. Finally, re-weighting is conducted. The observation error is calculated from the SNR. The data of strong sources and the baseline between large antennas are more heavily weighted in the analysis since their observation errors are minute. However, the residuals of $(O_i - C_i - \Delta C_i)$ regarding sources are almost the same in standard analysis since analysis errors and errors caused by atmospheric scintillation should be added to observation errors in additional to the noise error by SNR[13]. It is difficult to estimate an analysis error. In re-weighting, the formal error is added to the observation error for each baseline as an analysis error. Formal error is obtained by making the chi square equal 1 for each baseline.

4. Data Base Setup Software

The data base setup software inputs various data for VLBI into the data base. We originally developed this software. Figure 6 shows the algorithm for setting up the data into the data base.

The bandwidth synthesis software produces the files including the observation delay and delay rate for every occurrence (on each baseline for each observation). First, we collect the data from these files and produce a new observation data file whose record includes the necessary observation data for each occurrence at S/X bands. The data is used as the latest results of the bandwidth synthesis.

Secondly, we calculated the ionospheric delay and delay rate corrections on both S and X bands using the observation delay and delay rate on S and X bands as follows;

$$\Delta\tau_{ion}(X) = \frac{f_s^2}{f_s^2 - f_x^2}(\tau_x - \tau_s)$$
$$\Delta\tau_{ion}(S) = \frac{f_x^2}{f_s^2 - f_x^2}(\tau_x - \tau_s) \qquad (2)$$

these ionospheric corrections are used for the input into the ionospheric correction data file.

Thirdly, we calculate the ephemeris data such as the velocity of the earth barycenter at the solar barycentric coordinate and the distances between the earth, the moon and the sun using the JPL ephemeris "DE200/LE200." The data of the original JPL ephemeris are the coefficients of Tschebyscheff polynomial expressions which are fitted to the positions of the 9 planets, the moon and sun every 32 days. We need to calculate the ephemeris data for each occurrence and we input these data into the new ephemeris data file. The calculation method used to obtain the positions, velocities and acceleration for each observation was described in detail in the review of CRL[7].

Fourthly, the temperature, the atmospheric pressure, the humidity and the cable delay calibration are included in the log file of each station. The data are retrieved from the log file, and the interpolated data is calculated for each observation. The interpolated data is input into the new calibration data file for each station.

Fifthly, we prepare for the precise earth rotation parameters such as UT1 and wobble, and we set up the earth rotation parameters into the earth rotation parameter file. These constant interval data such as the 5 day data of IRIS (International Rotation Interferometry Surveying) are used in the software for the calculated delay to be interpolated for each observation.

Finally, we collect the data in the observation data file, the ionospheric correction file, the ephemeris data file, the new calibration data file and the earth rotation parameter file, and we set up all the data into the data base.

5. Data Converting System From K-3 to K-4 Tapes

A part of the experiments in the Western Pacific VLBI network project were conducted in cooperation with the CDP experiments. In that situation, NASA produced the correlation processing for MARK-III, and we had to prepare the observation tape for K-3 (MARK-III) type. In our observations, we observed by K-4 recorder at MARCUS station and CDP requested the MARCUS data. Therefore, we developed the data converting software from K-4 tape to MARK-III tape. Apart from the experiments of the Western Pacific VLBI network project, this software is used for many experiments which need the conversion from K-4 tape to MARK-III tape for both high and low density.

6. New Parameter Estimation Software

We developed the new parameter estimation software for the NEC computer system (ACOS) and HP work station (Apollo). This estimation method is almost the same as the estimation software (SOLVE). This software has the correction file. We conducted experiments with the 3 m antenna on Daito island. This antenna had only X band receiver, thus we should correct the ionospheric delay obtained by the separate ionospheric measurement system (TEC meter) using GPS. This new estimation software can correct the delay and delay rate using data from the correction file. This file also includes a bad data flag. Normally, the bad data is automatically determined by the SNR (Signal-to-Noise Ratio) and the quality code in the bandwidth synthesis, and it is also manually judged by the residuals after the baseline analysis.

7. Conclusion

We established a new data processing system and a new analysis system for the Western Pacific VLBI network project, and they are used for any VLBI experiments conducted by CRL. The computer system HP1000-A900 and personal computer HP9000-330 system were introduced. K-4 VLBI acquisition terminal was used in this project. We had develop the data processing software for the personal computer HP9000-330. This software is the first software which can make a correlation processing using K-4 recorders, and it is the only software system that can facilitate a mixing correlation processing between K-3 (MARK-III) and K-4 recorders.

The analysis software such as software to calculate the delay and delay rate, the parameter estimation software and the data base handler are basically the MARK-III type software developed by GSFC/NASA for the HP1000-A900 computer system. We developed the data base setup software by ourselves. These software systems were used not only in the Western Pacific VLBI network project but also for other experiments. Furthermore, the software used for converting from K-4 tape to MARK-III tape was also developed and it was used for many experiments.

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III. GEODETIC RESULTS OF THE EXPERIMENTS

III.1 MOVEMENT OF THE MINAMITORISHIMA STATION

By
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ABSTRACT

The motion of the Minamitorishima Very Long Baseline Interferometry station has been measured over the last five years in Western Pacific VLBI Network experiments. The results of 16 independent experiments indicated its steady motion of the station in the horizontal projection plane. The estimated velocity was 70.9 ± 3.0 mm/year toward N71.2 ± 2.2° W in the latest IERS Terrestrial Reference Frame, ITRF93. The high reliability and quality of the data obtained in the Western Pacific VLBI Network experiments was demonstrated by the estimated horizontal movement of the station being consistent with a constant-velocity linear motion.

1. Introduction

Minamitorishima island, lying in the Pacific Ocean at latitude 24°17′ N and longitude 153°59′ E, gives us a unique opportunity to study the behavior of the Pacific Plate because there are no other precise geodetic measurement sites in the northwestern region of the plate. A Very Long Baseline Interferometry (VLBI) station was established near the northern edge of the island in 1989 as one node of the Western Pacific VLBI Network (WPVN). Four nodes of this network—Minamitorishima, Kashima, Seshan, and Minamidaito—are shown in Fig. 1. Kashima and Seshan were already performing geodetic VLBI at the beginning of WPVN project, and the other two sites were chosen so that each node of the network is on a different plate. The Minamitorishima station is located far from the nearest plate boundary (≈800 km from that between Pacific Plate and the Philippine Sea Plate) and is thought to be out of the active deformation zone(1). The site velocity of the Minamitorishima station is thus considered to represent the motion of the Pacific Plate. Although there are many space geodetic stations on the Pacific Plate as shown in Fig. 2, many of them are located very close to the Pacific Plate-North American Plate boundary along the west coast of the United States. The plate boundaries in Fig. 2 are shown as narrow lines and some might argue about the location of these boundaries around Japan. As discussed by Gordon and Stein(1), however, plate boundaries are better described as variously wide zones of active deformation. Vandenberg and Fort Ord VLBI stations have been used in previous studies of the Pacific plate motion(2)-(6) under the assumption that these sites are on the stable interior of the Pacific Plate, but whether or not they are out of any active

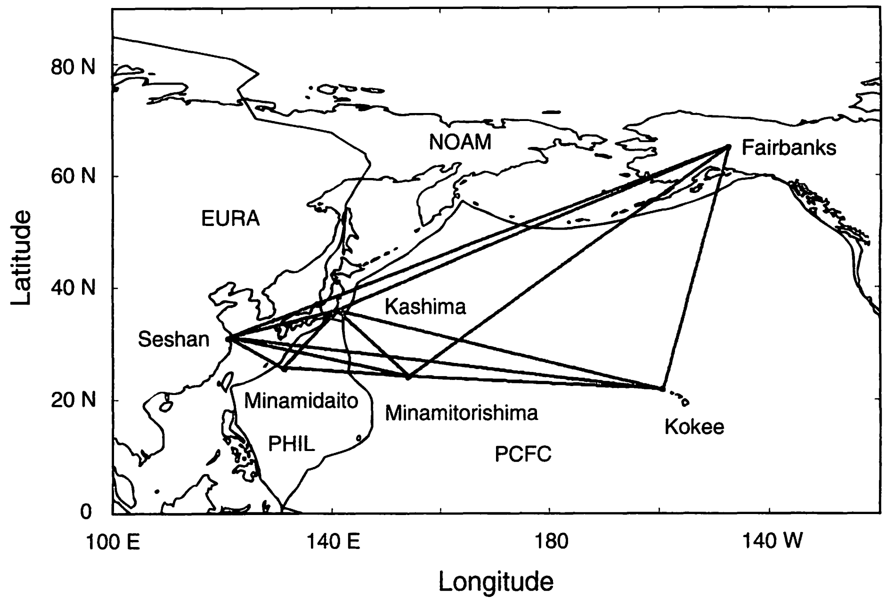

Fig. 1 Configuration of the Western Pacific VLBI network. Locations of Fairbanks station (Gilmore Creek Geophysical Observatory, Alaska) and Kokee station (Kokee Park Geophysical Observatory, Hawaii) are also shown. Lines indicating boundaries between the Eurasian Plate (EURA), the North American Plate (NOAM), the Philippine Sea Plate (PHIL), and the Pacific Plate (PCFC) are also shown.

deformation zone is not obvious. If these two stations are excluded, there were only two VLBI stations (Kauai and Kwajalein) and two SLR stations (Maui and Huahine) on the inner stable part of the Pacific Plate before Minamitorishima VLBI station was established. The addition of the site velocity data of the Minamitorishima VLBI station thus contribute a lot to the space geodetical study of Pacific Plate motion.

Since the first VLBI observations at Minamitorishima in July 1989, there has been 16 VLBI experiments involving the station (Table 1). Takahashi et al.[7] reported the first result of Minamitorishima VLBI station's site coordinate determined from two experiments in 1989, and a year later Koyama reported results of data analysis on two experiments in 1990[8]. Site velocity of the station estimated from all the 16 VLBI experiments was reported by Koyama et al[9], and the present paper reports the results of analyzing the same data set using the *a priori* parameters which became available in the annual report of International Earth Rotation Service (IERS)[10] and in the report of ITRF93[11].

2. Experiments

Nearly all the experiments performed at the Minamitorishima station were scheduled, considering the calm weather conditions at the site, for the end of June or beginning of July. The only exceptions were in the first year, when two sessions were performed on 24 July and on 11 August. All of necessary VLBI equipment (including a data acquisition terminal, a control computer and a

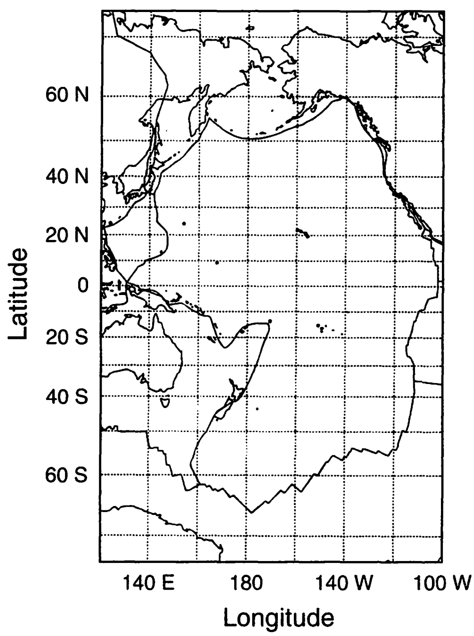

Fig. 2 Space Geodetic observation sites on the Pacific Plate (as specified in the ITRF93 site list).

frequency standard) system was transported to Minamitorishima from CRL before the first experiment each year and was kept on site for about a month. The frequency standard system used at Minamitorishima until 1992 was a hybrid system consisting of a highly stable crystal oscillator and a Cesium beam standard frequency source, whereas a hydrogen maser system was used in the three experiments in 1993. Each year, two experiments were scheduled as regular series with a three-station (Kashima, Seshan, and Minamitorishima) configuration. In 1991, five additional experiments were scheduled with a two-station (Kashima and Minamitorishima) configuration. An experiment with a five-station (Kashima, Seshan, Kokee, Fairbanks, and Minamitorishima) configuration was also organized in 1993. Since the Fairbanks station participated in the first session in 1990, there are two baseline length data for the Fairbanks-Minamitorishima baseline, whereas there is only one baseline length datum for the Kokee-Minamitorishima baseline.

Observation schedules for WPVN experiments were generated at Kashima Space Research Center of CRL, using the software SKED developed by Goddard Space Flight Center (GSFC) of the National Aeronautics and Space Agency (NASA). For experiments held in 1989–1992, the observation scan length was kept short (ranging from 150 to 196 seconds) because the frequency of the Crystal-Cesium system does not remain sufficiently stable during longer integration times. Because of this restriction, only strong radio sources were chosen. For the experiments in 1993, each observation scan length was determined to satisfy a certain signal-to-noise ratio, 20 for the X band and 15 for the S band calculated from the given flux densities of radio sources. This became possible in 1993 when a Hydrogen maser frequency standard system was transported to the station. In addition, SKED was revised by GSFC to generate schedule files automatically by optimizing the estimation of desired parameters. For the experiments in 1993, we used this function to optimize the observation schedules to minimize the estimation errors for Minamitorishima site position.

Table 1 VLBI sessions for the Minamitorishima station

Date	Stations
1989.7.24	Kas26[a], Minamitosrishima, Seshan
1989.8.12	Kas26, Minamitorishima, Seshan
1990.6.25	Kas34[b], Kas26, Minamitorishima, Seshan, Fairbanks
1990.6.30	Kas34, Kas26, Minamitorishima, Seshan
1991.6.27	Kas34, Minamitorishima
1991.6.28	Kas34, Minamitorishima
1991.6.30	Kas34, Minamitorishima, Seshan
1991.7.01	Kas34, Minamitorishima
1991.7.02	Kas34, Minamitorishima
1991.7.03	Kas34, Minamitorishima
1991.7.04	Kas34, Minamitorishima, Seshan
1992.6.25	Kas34, Minamitorishima, Seshan
1992.6.28	Kas34, Minamitorishima, Seshan
1993.6.24	Kas34, Minamitorishima, Seshan
1993.6.26	Kas34, Minamitorishima, Seshan
1993.6.28	Kas34, Minamitorishima, Seshan[c], Kokee, Fairbanks

a.) Kas34 = 34 m antenna at Kashima
b.) Kas26 = 26 m antenna at Kashima
c.) A preliminary database without Seshan was used for analysis

Experiments were basically successful but some portions of experiments were lost for various reasons. A special case was that the S band phase-cal signal was affected by spurious radiation from the receiving system. This prevented S band data gathered in the 1989 experiments from being used for the usual bandwidth synthesis processing. To solve this problem, the phase-cal signal phase in each frequency channel was fixed to its average value. This procedure successfully removed the effect of ionospheric delay from the data which are otherwise not as accurate as the data gathered in the following years.

3. Data Analysis

Data were analyzed by using the geodetic VLBI analysis software package CALC version 7.6 and SOLVE developed by GSFC[12]. Since our primary intention was to estimate the site velocity of Minamitorishima VLBI station, we specified as many *a priori* parameters as possible: Earth rotation parameters (position of Earth's rotation pole with respect to a conventional pole, UT1-UTC, and an offset of celestial pole from the conventional celestial pole defined by the 1980 IAU Theory of Nutation), radio source coordinates, and site coordinates of three VLBI stations (Kashima, Seshan, and Fairbanks). This strategy is not common in usual geodetic VLBI data analysis where these values (except for a minimum set of defined parameters to resolve an arbitrariness) are also subject of estimation in the data analysis. In our case, however, considering the limited number of experiments performed at the Minamitorishima station and its poor sensitivity compared to that of the other stations, it does not seem worthwhile to follow the way of usual data analysis. This poor sensitivity

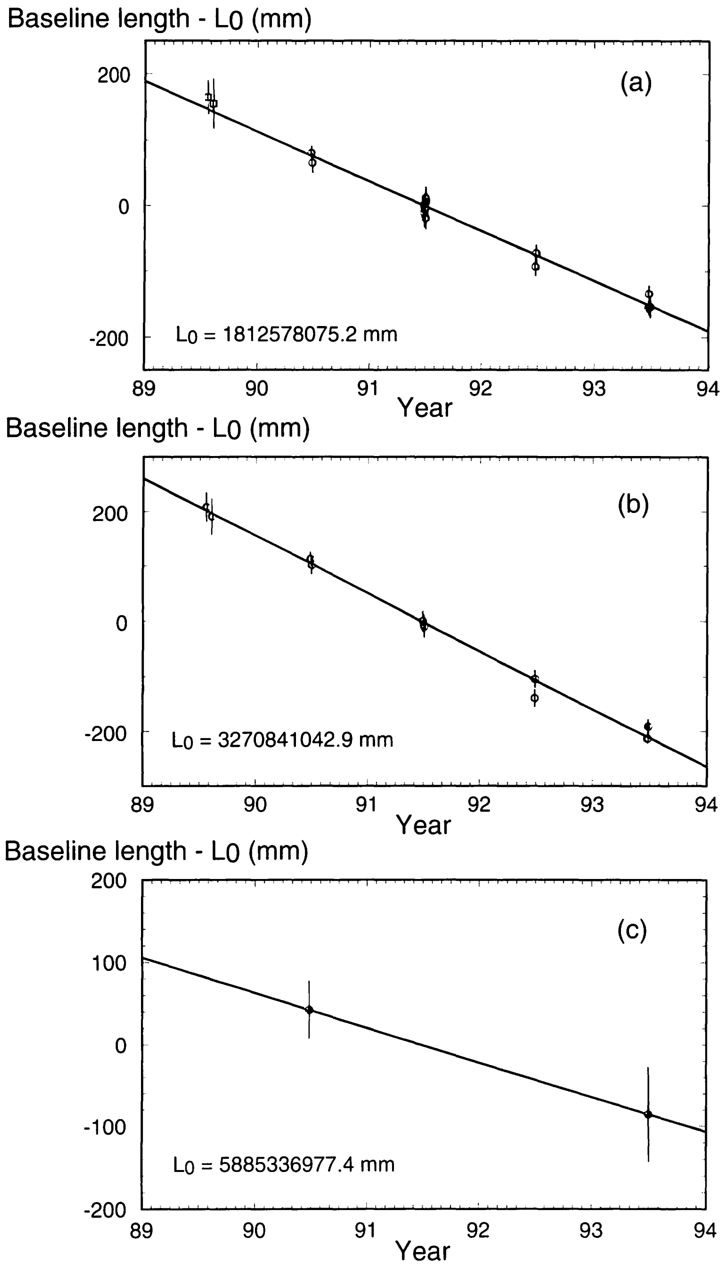

Fig. 3 Baseline length plots from WPVN experiments. Each point is plotted with 1 σ error bar. Straight lines are results of least-squares estimations by assuming a constant change of each baseline length. Two open squares in the Kas34-Minamitorishima baseline plot indicate these data were actually calculated from Kas26-Minamitorishima baseline lengths.

Table 2 Site coordinates of Minamitorishima VLBI station estimated from 16 VLBI experiments. Uncertainties are expressed by one standard deviations scaled by the square roots of the reduced chi-squares.

Date	Site coordinates (mm)			Correlation factors		
	x	y	z	x-y	x-z	y-z
1989.7.24	−5227446754.4 ±75.6	2551379274.6 ±51.1	2607604788.5 ±55.8	−0.86	−0.86	0.88
1989.8.12	−5227446632.0 ±104.0	2551379177.6 ±76.9	2607604730.7 ±83.4	−0.90	−0.86	0.94
1990.6.25	−5227446733.7 ±31.1	2551379326.6 ±15.9	2607604847.2 ±21.2	−0.79	−0.80	0.69
1990.6.30	−5227446729.3 ±39.3	2551379333.7 ±23.4	2607604861.4 ±27.4	−0.78	−0.79	0.79
1991.6.27	−5227446668.9 ±37.5	2551379375.5 ±26.8	2607604850.2 ±30.7	−0.79	−0.83	0.88
1991.6.28	−5227446763.0 ±50.2	2551379456.0 ±35.0	2607604919.8 ±39.6	−0.77	−0.81	0.87
1991.6.30	−5227446651.6 ±40.4	2551379350.4 ±23.9	2607604849.8 ±27.1	−0.75	−0.79	0.77
1991.7.01	−5227446664.0 ±40.7	2551379391.8 ±29.4	2607604841.7 ±33.4	−0.78	−0.80	0.87
1991.7.02	−5227446631.3 ±38.7	2551379361.7 ±29.1	2607604799.2 ±33.0	−0.80	−0.81	0.89
1991.7.03	−5227446693.5 ±35.2	2551379403.0 ±25.2	2607604891.3 ±28.9	−0.78	−0.80	0.87
1991.7.04	−5227446682.0 ±46.0	2551379400.7 ±28.5	2607604838.6 ±30.4	−0.79	−0.79	0.79
1992.6.25	−5227446614.5 ±38.5	2551379459.9 ±23.1	2607604863.7 ±25.7	−0.80	−0.81	0.81
1992.6.28	−5227446698.8 ±36.7	2551379488.3 ±28.5	2607604905.4 ±18.6	−0.79	−0.82	0.81
1993.6.24	−5227446631.1 ±28.4	2551379517.6 ±18.4	2607604922.7 ±16.8	−0.80	−0.81	0.82
1993.6.26	−5227446626.5 ±32.5	2551379484.3 ±20.3	2607604904.2 ±19.2	−0.79	−0.77	0.77
1993.6.28	−5227446508.0 ±45.0	2551379459.6 ±24.4	2607604821.6 ±31.9	−0.73	−0.72	0.40

comes partly from the relatively small aperture of the antenna and the limited integration time (~180 sec) due to the instability of the composite frequency standard system used from 1989 through 1992. This instability also requires more estimated clock epochs and causes a larger scatter in the residual of observed time delay. Using a large number of *a priori* parameters, on the other hand, risks inconsistency between them and the models on which the analysis relies, such as series of precession and nutation values and a model of site displacement due to ocean tides. Since inconsistent *a priori* parameters may produce inadequate results, it is important that their consistency and credibility be maintained over the period of experiments. IERS has been playing a central role in providing such consistent parameters and standard models, but in a sense of uniformity throughout the period of WPVN experiments, truly uniform series of Earth rotation parameters did not become available until

Table 3 Lengths of four baselines towards Minamitorishima station estimated from 16 VLBI experiments. Uncertainties are expressed by one standard deviations scaled by the square roots of the reduced chi-squares.

Date	Minamitorishima-Kas26 (mm)	Minamitorishima-Kas34 (mm)	Minamitorishima-Seshan (mm)	Minamitorishima-Fairbanks (mm)
1989.7.24	1812270600.66 ±25.3		3270841252.1 ±26.8	
1989.8.12	1812270591.23 ±37.6		3270841235.4 ±33.8	
1990.6.25	1812270516.30 ±10.8	1812578156.0 ±10.8	3270841157.3 ±13.2	5885336998.9 ±17.4
1990.6.30	1812270501.68 ±15.4	1812578141.2 ±15.4	3270841146.1 ±17.1	
1991.6.27		1812578076.1 ±15.9		
1991.6.28		1812578064.9 ±21.7		
1991.6.30		1812578078.8 ±15.9	3270841045.0 ±18.2	
1991.7.01		1812578071.3 ±18.3		
1991.7.02		1812578087.4 ±17.5		
1991.7.03		1812578056.3 ±15.7		
1991.7.04		1812578081.8 ±17.6	3270841035.3 ±19.7	
1992.6.25		1812577982.8 ±14.1	3270840906.4 ±16.1	
1992.6.28		1812578002.9 ±13.2	3270840940.8 ±15.4	
1993.6.24		1812577920.3 ±10.4	3270840832.3 ±11.9	
1993.6.26		1812577941.8 ±12.6	3270840854.1 ±14.1	
1993.6.28		1812577922.1 ±16.5		5885336934.8 ±29.0

the recent release of the 1993 Annual Report of IERS[10]. We used this data set for *a priori* parameters, and we used the recent realization of standard models provided as IERS standards (1992)[13]. Although the ocean tide coefficients for Minamitorishima and Seshan are not available from IERS standards (1992), they were obtained from Scherneck[14] by using the same model as in the IERS standards (1992). ITRF93 is a set of site coordinates and velocities that define a terrestrial reference frame, whereas ICRF93 is a set of radio source coordinates that define a celestial reference frame. ITRF93 was produced by a combination of independent analyses of data from three space geodetic techniques (VLBI, SLR, and GPS). Site coordinates of Kashima, Seshan, and Fairbanks were obtained from ITRF93 throughout the data analysis and only the Minamitorishima and Kauai site velocities were estimated. ICRF93 was also produced by a combination of independent data

Table 4 Lengths of three baselines towards Minamitorishima station and their rates of change. Uncertainties are expressed by the one standard deviations scaled by the square roots of the reduced chi-squares.

Baseline	Baseline length on 1991.5 (mm)	Rate (mm/year)	Reduced χ^2
Kas34-Minamitorishima	1812578075.2 ± 3.0	−75.9 ± 2.4	0.522
Seshan-Minamitorishima	3270841042.9 ± 5.1	−104.9 ± 3.7	0.854
Fairbanks-Minamitorishima	5885336977.4 ± 15.1	−21.3 ± 11.3	...

analyses but only from VLBI. Coordinates of all the radio sources observed in the WPVN experiments were fixed to the values from ICRF93. EOP93C02 is a series of Earth rotation parameters at five-day intervals through the end of 1993. These values, too, were derived from a combination of independent data analyses from three space geodetic techniques consistently with the ITRF93, ICRF93 and the IERS standards (1992). Interpolation of UT1-UTC was performed after removing short-term variation due to the ocean tides by using coefficients defined in IERS92 standards, and the same term was added again after the interpolation. The CALC software, which calculates theoretical time delays and their time derivatives based on *a priori* information and sets up a Jacobian matrix for the least-squares parameter adjustment to be performed by SOLVE, uses IERS standards (1992) and thus maintains the consistency with specified *a priori* parameters.

4. Results

Table 2 gives the three-dimensional site coordinates for Minamitorishima VLBI station at the date of each session obtained after data analyses of 16 individual VLBI experiments. These site coordinates can be treated to be based on the ITRF93 terrestrial reference frame. Uncertainties in the table are one standard deviations scaled by the square root of the chi square estimated through the least-squares analysis. Correlation factors between the three components are also given for each experiment. Table 3 lists the lengths of four baselines towards Minamitorishima VLBI station. Uncertainties are the scaled one sigma standard deviations same as the case for the site coordinate results in Table 2. Values in Table 3 are also plotted in Fig. 3, where three baselines (except for Kas26-Minamitorishima) are shown. Instead, two sets of data for Kas26-Minamitorishima baseline length in 1989 are transferred to Kas34-Minamitorishima length by adding 307.6397 m, which is the difference of lengths between these two baselines according to the ITRF93 coordinates on 1993.0. A least-square estimation was used to obtain an epoch value and a rate of change for each baseline. Table 4 shows these results.

A site coordinate at an arbitrary epoch and a velocity can be estimated by the least-squares criteria. If we assume that the site is moving with a constant velocity, the obtained site position $\mathbf{r}_i$ from i-th VLBI session at the time t_i can be expressed by

$$\mathbf{r}_i = \mathbf{r}_0 + \mathbf{v}(t_i - t_0) + \mathbf{d}_i \qquad (1)$$

where $\mathbf{r}_0$ is the site position at the time epoch t_0 and $\mathbf{v}$ is the site velocity. The term $\mathbf{d}_i$ is a residual of the estimated site position from the $\mathbf{r}_0 + \mathbf{v}(t_i - t_0)$. The error matrix of the $\mathbf{r}_i$ is defined by

$$\Sigma_i = \begin{pmatrix} \sigma_{xi}^2 & \rho_{xyi}\sigma_{xi}\sigma_{yi} & \rho_{xzi}\sigma_{xi}\sigma_{zi} \\ \rho_{xyi}\sigma_{xi}\sigma_{yi} & \sigma_{yi}^2 & \rho_{yzi}\sigma_{yi}\sigma_{zi} \\ \rho_{xzi}\sigma_{xi}\sigma_{zi} & \rho_{yzi}\sigma_{yi}\sigma_{zi} & \sigma_{zi}^2 \end{pmatrix} \quad (2)$$

where (σ_{xi}, σ_{yi}, σ_{zi}) and (ρ_{xyi}, ρ_{xzi}, ρ_{yzi}) are one standard deviations of site coordinates and correlation factors between site coordinates, respectively, estimated from the data analysis. The estimates of $\mathbf{r}_0$ and $\mathbf{v}$, which we denote $\hat{\mathbf{r}}$ and $\hat{\mathbf{v}}$, are given by minimizing the sum of weighted square of the $\mathbf{d}_i$. Here the weighted squared $\mathbf{d}_i$ is given by $d_i^T \Sigma_i^{-1} \mathbf{d}_i$. The transverse of a matrix, or a vector in this case, is denoted by a superscript 'T'. The solution is given by

$$\begin{pmatrix} \hat{\mathbf{r}}_0 \\ \hat{\mathbf{v}} \end{pmatrix} = \left(A^T W_1 A\right)^{-1} A^T W_1 R \quad (3)$$

where

$$R = \begin{pmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \vdots \\ \mathbf{r}_n \end{pmatrix} \quad (4)$$

$$A = \begin{pmatrix} 1\,0\,0 & t_1 - t_0 & 0 & 0 \\ 0\,1\,0 & 0 & t_1 - t_0 & 0 \\ 0\,0\,1 & 0 & 0 & t_1 - t_0 \\ 1\,0\,0 & t_2 - t_0 & 0 & 0 \\ 0\,1\,0 & 0 & t_2 - t_0 & 0 \\ 0\,0\,1 & 0 & 0 & t_2 - t_0 \\ \vdots & & \vdots & \\ 1\,0\,0 & t_n - t_0 & 0 & 0 \\ 0\,1\,0 & 0 & t_n - t_0 & 0 \\ 0\,0\,1 & 0 & 0 & t_n - t_0 \end{pmatrix} \quad (5)$$

and

$$W_1 = \begin{pmatrix} \Sigma_1^{-1} & & & 0 \\ & \Sigma_2^{-1} & & \\ & & \ddots & \\ 0 & & & \Sigma_n^{-1} \end{pmatrix} \quad (6)$$

Table 5 Minamitorishima site coordinate in the ITRF93 reference frame and in the local NEU coordiante system. The origin of the local reference system is taken to be the 1993.0 site coordinate given in the ITRF93.

[Epoch] Component	Value (mm)	Correlation		Rate (mm/year)	Correlation	
[1991.5]						
x	−5227446679.5 ± 10.3	x–y	−0.790	35.9 ± 8.8	x–y	−0.802
y	2551379386.5 ± 6.3	x–z	−0.799	57.2 ± 5.3	x–z	−0.792
z	2607604856.9 ± 7.1	y–z	0.811	21.9 ± 5.6	y–z	0.780
n	−17.6 ± 3.9	n–e	−0.331	22.9 ± 2.9	n–e	−0.227
e	91.7 ± 3.6	n–u	0.327	−67.1 ± 2.8	n–u	0.161
u	−61.9 ± 13.5	e–u	−0.181	2.5 ± 11.0	e–u	−0.154
[1993.0]						
x	−5227446626.6 ± 13.4	x–y	−0.790	35.9 ± 8.8	x–y	−0.802
y	2551379473.4 ± 8.3	x–z	−0.799	57.2 ± 5.3	x–z	−0.792
z	2607604891.3 ± 8.0	y–z	0.811	21.9 ± 5.6	y–z	0.780
n	19.34 ± 4.2	n–e	−0.210	22.9 ± 2.9	n–e	−0.227
e	−10.79 ± 4.6	n–u	0.051	−67.1 ± 2.8	n–u	0.161
u	−51.87 ± 16.5	e–u	−0.183	2.5 ± 11.0	e–u	−0.154

This procedure was used to estimate the site velocity and site coordinates at two time epochs (1991.5 and 1993.0), and these values are presented in Table 5. The time epoch at 1991.5 gives a minimal uncertainty of $\mathbf{r}_0$ because it is nearly the middle of the period in which the 16 sessions were performed. The estimate at the epoch 1993.0 was also given to follow ITRF93 specification where all the site coordinates are specified at the epoch 1993.0. The site velocity estimate remains unchanged regardless of the selection of t_0. The chi-square (χ^2) of the least-squares fit was calculated as

$$\chi^2 = \mathrm{B}^{\mathrm{T}}\mathrm{W}_1\mathrm{B} \quad \mathrm{B} = \mathrm{R} - \mathrm{A}\begin{pmatrix}\hat{\mathbf{r}}_0 \\ \hat{\mathbf{v}}\end{pmatrix} \qquad (7)$$

This value is calculated as 50.7 which, divided by the 42 degrees of freedum, gives the reduced chi-square (χ^{-2}) of 1.21. 95% of the reduced chi-square statistically distribute between 0.62 and 1.47 in the case where the degree of freedum is 42. The fact that the reduced chi-square is very close to a unity indicates two things. First, the uncertainties given in Table 2 were adequately evaluated. Second, the assumption that the site is linearly moving with a constant velocity was consistent with the observed time series of site positions. This result is rather exceptional, since there is a tendency in various VLBI data analyses for the reduced chi-square to be significantly greater than unity and for the uncertainties obtained to be underestimated. One possible explanation of the large reduced chi-square is an annual fluctuation of site coordinate estimates as a result of unmodeled seasonal variation, such as a tropospheric delay. Such an annual fluctuation, would cause systematic but similar errors in the 16 site coordinate estimates and thus the estimated site velocity would not be affected because all the VLBI sessions for Minamitorishima were done in the same season of a year.

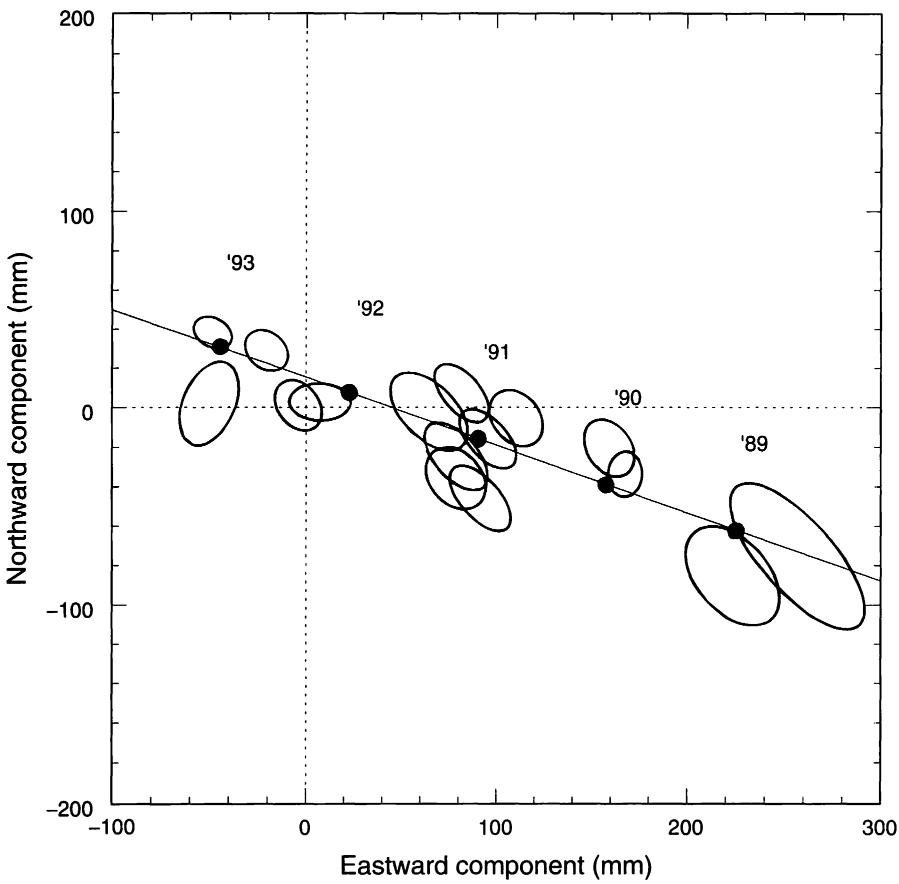

Fig. 4 Estimated Minamitorishima site position projected on to the horizontal plane with the origin of the 1993.0 position of the Minamitorishima site according to ITRF93. Each point is plotted with 1 σ error ellipse. Straight line and five dots on the line indicate linear motion of the site and site positions on 1989.5, 1990.5, 1991.5, 1992.5, and 1993.5 calculated from the least-squares estimation.

Table 5 also gives the same site velocity expressed in the local coordinate system defined by east, north, and vertically upward directions. According to these results, the horizontal movement of the Minamitorishima station is 70.9 ± 3.0 mm/year toward N71.2 ± 2.2° W. The estimated site positions of Minamitorishima VLBI station listed in Table 2 are shown in Fig. 4 projected on the horizontal plate. The estimated epoch positions and velocities in the local coordinate system listed in Table 5 are expressed in Fig. 4 by a gray line with five dots on the line indicating the epoch positions of the site on 1989.5, 1990.5, 1991.5, 1992.5, and 1993.5.

5. Conclusions

The movement of the Minamitorishima station is evident in both the baseline length data and station positions projected on the horizontal plane. On the other hand, vertical movement was not evident given under our limit of vertical position uncertainties. As shown in Fig. 3, the lengths of Kas34-Minamitorishima and Seshan-Minamitorishima baselines are well represented by linear functions of time. These data are consistent with the station moving horizontally with a constant velocity. The results also demonstrated the high reliability and quality of the data obtained from WPVN experiments. Values of reduced χ^2 in Table 4 can be used to evaluate the quality of the least-squares estimate and are very close to and even smaller (better) than unity. This suggests that the assumption that the Minamitorishima station is moving linearly with a constant velocity is correct (within the present uncertainties of estimates), and that the estimated uncertainties of data are consistent with the repeatability of measurements.

Residual RMS values can be considered to represent the repeatability of the obtained data, and these values indicate that horizontal components of the Minamitorishima station position and baseline lengths were determined with an uncertainty of 4 mm, whereas the vertical component was determined with an uncertainty of 13 mm. It is also seen that data from experiments in 1989 are not as good as the other years. This is thought to be an effect of the problem in S band interference signal that year.

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III. GEODETIC RESULTS OF THE EXPERIMENTS

III.2 MOVEMENT OF THE MINAMIDAITO STATION

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ABSTRACT

Geodetic VLBI experiments on the baselines including Minamidaito island were carried out in 1990 and 1991. This was the first attempt to measure the movement of the Philippine Sea plate in multibaseline VLBI experiments. The data obtained in these experiments was used to estimate the Philippine sea plate motions relative to the Eurasian plate and the North American plate. The estimated plate velocity is greater than that derived from seismological data and the results of GPS observations. The direction of the observed movement of Minamidaito relative to the Eurasian plate is N78.1° W and close to the result obtained by GPS measurement.

Keywords: Minamidaito, VLBI, Philippine Sea plate, ionospheric delay

1. Introduction

Minamidaito is located on the Philippine Sea plate (PH, see Fig. 1). The movement of the PH had not been confirmed by direct measurement until 1989. There had been only predictions derived from earthquake slip vectors[1]. The first attempts to measure the motion of the PH were performed by VLBI on the baseline between Kashima and Chichijima in 1987 and 1989[2], and results agreed within two-sigma with the prediction of Seno et al.[1]. Because these experiments were carried out on the baseline whose direction was different from the expected relative movement of the station, they derived the plate motion only from the vector change, which is easily affected by the uncertainties of the earth orientation parameter. Recently, however, GPS measurements were carried out at Minamidaito, with islands of the Ryukyu Arc. These measurements have been made annually since 1990, and initial results indicate that velocity of Minamidaito relative to the Ryukyu Arc is 8.7 ± 3.1 cm/yr and that the direction of this motion is N70° W[3].

The Communications Research Laboratory (CRL) in November 1990 and December 1991 conducted VLBI experiments on the baselines connecting Minamidaito, Kashima, and Shanghai. The Kashima and Shanghai stations are nominally located on the North American plate (NA) and the Eurasian plate (EU), respectively. These plates and the PH adjoin each other. Since the positions and velocities of Kashima and Shanghai stations have been precisely determined in the worldwide VLBI

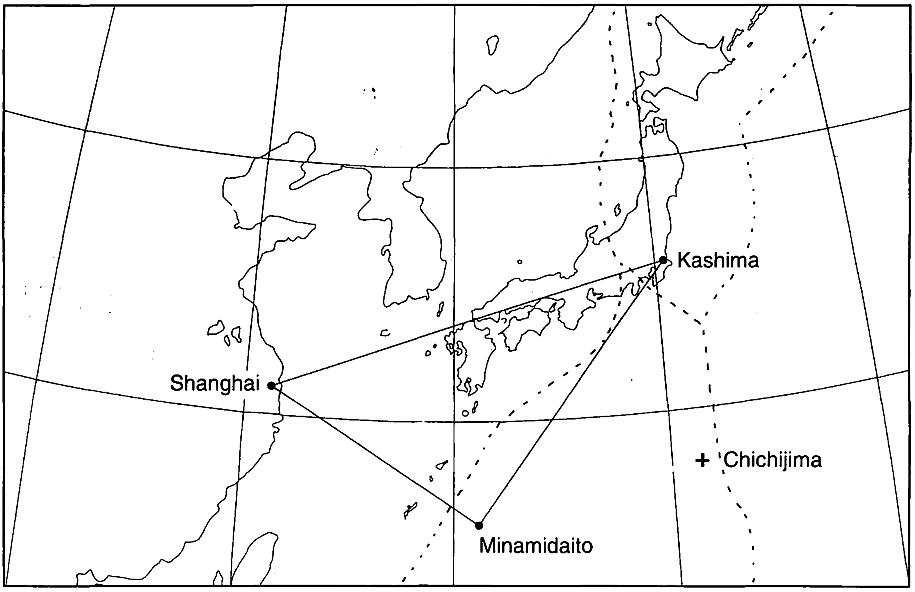


Fig. 1 Locations of the stations

terrestrial reference system by international VLBI experiments[4], we can treat these stations as references for the baseline analysis. The Shanghai-Minamidaito baseline is suitable for measurement of the relative motion of PH with EU because the direction of baseline vector is close to that of the relative plate motion expected.

The highly transportable VLBI station (HTVS)[5][6] developed by the CRL was used for Minamidaito. The HTVS is equipped only with an X band receiving system. Ionospheric delay corrections for the baselines including HTVS were performed by using the data of total electron contents of the ionosphere (TEC) observed by a TECMETER[7]. Unfortunately, since the quality of the TEC data observed at individual stations was not good, ionospheric delay corrections for the data of the baselines including Minamidaito were not satisfactory. The estimated position of Minamidaito is thought to be affected by the ionospheric delay corrections adopted inadequately.

2. Experimental Conditions

Four VLBI observing sessions have been carried out, and the experimental conditions of each session are summarized in Table 1. In addition to the Minamidaito and Kashima stations, which participated in each session, the Shanghai station joined in experiment sessions SDE90B and SDE91A.

We transported the HTVS to Minamidaito before SDE90A, to avoid effects of reinstalling it, the HTVS was kept fixed until all the experiments were completed. HTVS uses a 3 m antenna with a receiving bandwidth greater than that of the usual VLBI systems, a compact data acquisition system, and a compact frequency standard consisting of a cesium frequency standard and a high quality quartz oscillator. The low sensitivity due to the small antenna aperture and unstable frequency standard is largely compensated by using a larger receiving bandwidth. The HTVS receives signals in

Table 1 Summary of experiments

Code	Date	Stations
SDE90A	26 November 1990	Minamidaito, Kashima
SDE90B	28 November 1990	Minamidaito, Kashima, Shanghai
SDE91A	3 December 1991	Minamidaito, Kashima, Shanghai
SDE91B	5 December 1991	Minamidaito, Kashima

Table 2 Specifications of the stations

	Minamidaito	Kashima	Shanghai
Antenna diameter	3 m	34 m	25 m
Aperture efficiency	40%	68%	50%
System noise	120 K	52 K	100 K
Receiving band	Wide X	Wide X, S	Wide X, S ('90) Normal X, S ('91)
Frequency standard	Cs + X'tal	H Maser	H Maser
Video bandwidth		2 MHz each	

a lower part of the X band (7860 MHz to 8280 MHz) in addition to the conventional X band signals (8180 MHz to 8600 MHz) widely used for geodetic VLBI. The effective bandwidth of the HTVS is therefore about 1.6 times larger than that of the usual VLBI systems. The number of video channels used for the bandwidth synthesis is also increased: from 8 to 14. Although the HTVS does not use the S band receiving system for ionospheric delay correction, this correction can be done by using the TEC data obtained by a TECMETER.

The Kashima station uses a receiving band as wide as the one the HTVS uses, but Shanghai originally had only a normal bandwidth receiver. An additional lower X band receiving system was therefore transported to Shanghai from Kashima and installed in the system for one of the sessions in 1990 (SDE90B). Every station participated in SDE90B use wideband receivers and TECMETERs.

For the session of 1991 (SDE91A), the wide band was received for the Minamidaito-Kashima baseline but the Shanghai station observed only the normal receiving band signal. Ionospheric delay correction for the baseline with Minamidaito was done by TECMETER and for the Kashima-Shanghai baseline was done by the S-X dual band method.

3. Analysis

The raw data were cross-correlated at Kashima, and the correlation functions obtained were further processed using the bandwidth synthesis software to calculate the time delay and delay rates. The baseline analysis with the LOCAL software system was also performed at Kashima.

The dry components of the tropospheric delays were calculated by using the model of Saastamoinen(8) and the CFA2.2 mapping function(9). The wet component of tropospheric delay to the zenith direction was estimated as a linear function of time with breaks every 3 hours. To prevent an artificial sharp bend in the atmospheric zenith delay from being estimated, a continuity constraint

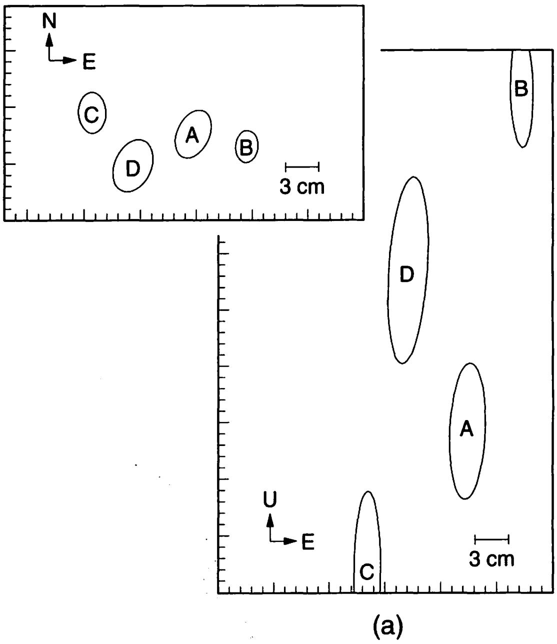
Table 3 Frequency arrangements used for the experiments

	SDE90A, SDE90B, SDE91B	SDE91A (Daito, Kashima 1)	SDE91A (Shanghai, Kashima 2)
Channel 1	7894.99 MHz	7894.99 MHz	8214.99 MHz
Channel 2	7904.99 MHz	7904.99 MHz	8224.99 MHz
Channel 3	7934.99 MHz	7984.99 MHz	8254.99 MHz
Channel 4	7984.99 MHz	8044.99 MHz	8314.99 MHz
Channel 5	8054.99 MHz	8104.99 MHz	8424.99 MHz
Channel 6	8104.99 MHz	8154.99 MHz	8504.99 MHz
Channel 7	8214.99 MHz	8214.99 MHz	8554.99 MHz
Channel 8	8234.99 MHz	8224.99 MHz	8574.99 MHz
Channel 9	8274.99 MHz	8254.99 MHz	2217.99 MHz
Channel 10	8344.99 MHz	8314.99 MHz	2222.99 MHz
Channel 11	8404.99 MHz	8424.99 MHz	2237.99 MHz
Channel 12	8494.99 MHz	8504.99 MHz	2267.99 MHz
Channel 13	8544.99 MHz	8554.99 MHz	2292.99 MHz
Channel 14	8564.99 MHz	8574.99 MHz	2302.99 MHz
Summary of X band			
Number of channels	14	14	8
Mean frequency	8211.42 MHz	8225.70 MHz	8383.74 MHz
RMS freq. (FRMS)	228.99 MHz	220.31 MHz	140.22 MHz
FRMS*SQRT(N)	856.81 MHz	824.31 MHz	396.60 MHz
Summary of S band			
Number of channels	NONE	NONE	6
Mean frequency			2257.16 MHz
RMS freq. (FRMS)			33.09 MHz
FRMS*SQRT (N)			81.06 MHz

with a tolerance value of 50 ps/hr/epoch was introduced. The cable length between a receiver system and ground system was always monitored at every station by using a delay calibrator, and the cable length data were used in the analysis.

The earth orientation parameters (i.e. UT1-UTC and the position of earth's rotation pole) were fixed to the *a priori* values obtained from the monthly bulletin of IERS (IERS bulletin B). To ensure the consistency of the reference frames, ITRF90 was used as the terrestrial reference frame and ICRF was used as the celestial reference frame. Kashima station and Shanghai station had carried out many CDP VLBI experiments and the positions and velocities of the antennas had been determined precisely. For these stations the positions and velocities were calculated and not estimated. These calculations were based on the site position of the ITRF90 system at the epoch of 1988.0 and used the site velocity obtained from GSFC solution GLB659(10).

Ionospheric delay corrections for the baseline including Minamidaito were performed using TEC data obtained by a TECMETER. TEC data measured by a TECMETER are not directly observed along the line-of-sight toward the observed radio source but those toward the GPS satellites, so the TECs obtained for GPS directions were projected to the radio star directions using the projection model developed by Kondo(7).



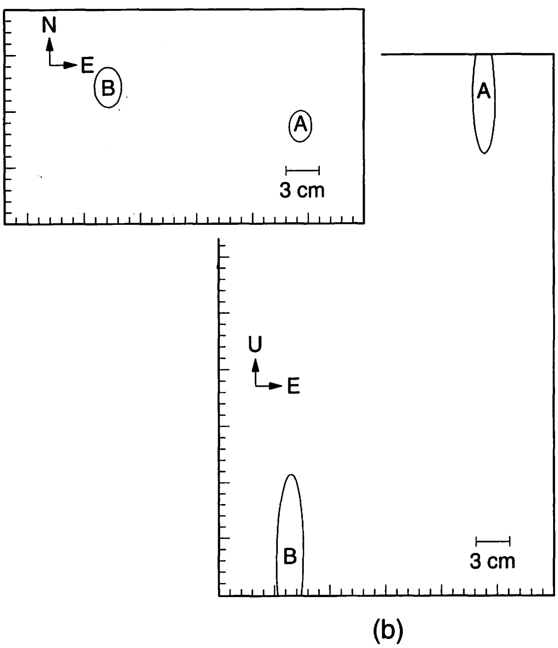
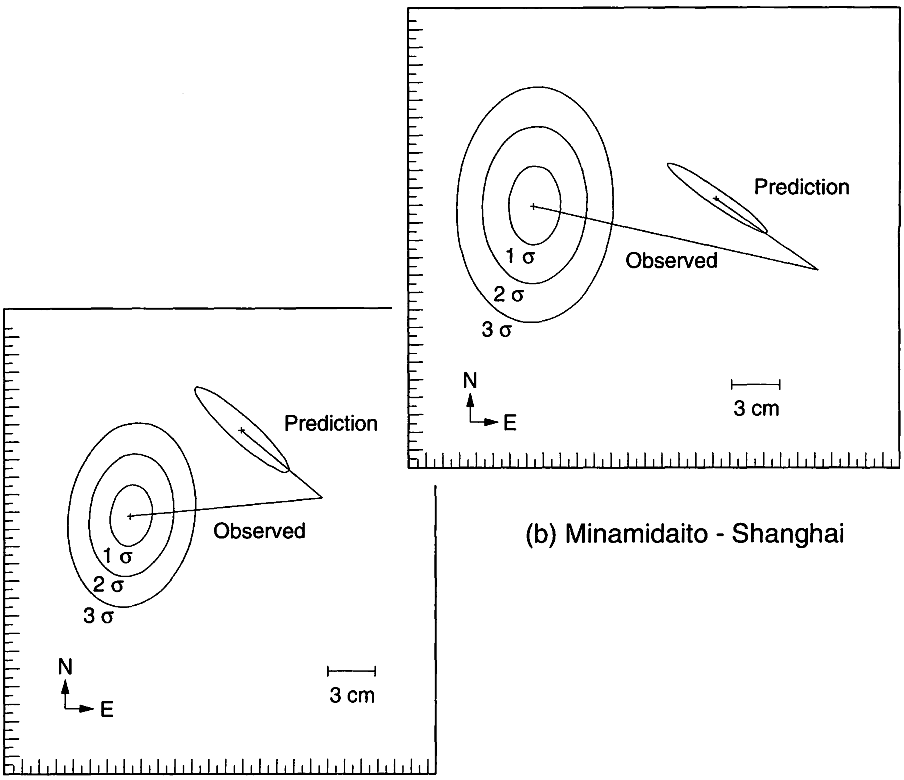


Fig. 2 Estimated positions of Minamidaito for each experimental session: (a) relative to Kashima station, (b) relative to Shanghai station. The letters A to D respectively denote SDE90A, SDE90B, SDE91A, and SDE91B.



(b) Minamidaito - Shanghai

(a) Minamidaito - Kashima

Fig. 3 Movement of Minamidaito station relative to (a) Kashima station, (b) Shanghai station.

Because only 16 GPS satellites were available at the time of the VLBI sessions and the distribution of the satellites were not uniform, not enough good TEC data were obtained to enable precise ionosphere delay corrections.

4. Geodetic Results

The estimated position of Minamidaito for each experiment is shown in Fig. 2. The vertical positions have a large scatter, which might be due to inadequate ionospheric delay correction. Figure 3 shows the relative movements of Minamidaito horizontal position calculated by comparing the positions at two epochs. The movements calculated from PH-EU and PH-PA relative rotation vectors predicted by Seno et al.[1] are also shown in the figure. Local movements of Kashima and Shanghai were not taken account in these predicted movements. The observed station velocity is more than twice the velocity predicted. Since the error of ionospheric delay estimated from TEC data is not accounted for in the baseline analysis, the error of the estimated station movements is thought to be smaller than the practical error. Nevertheless this disagreement between observed and predicted movements is too large to be explained by the local movements of Kashima and Shanghai station (which is less than 3 cm/yr[11][12]) or by the Earth orientation parameter error (which is less than 1 cm for a 1000 km baseline). The observed direction of the station movement is closer to westerly than the direction predicted by Seno et al.[1]. These tendencies, larger velocity and westerly direction, also appeared in the results of the GPS observation[3].

5. Conclusions

Our VLBI experiments on the baselines with Minamidaito indicated a larger velocity and more westerly direction than had been expected, but the inadequately corrected ionospheric delays may have affected the estimated station positions. We thus cannot further discuss crustal movement using these short period measurement results. To determine the velocity of the movement of Minamidaito precisely, future VLBI/GPS measurements must be performed.

6. Acknowledgments

We thank the staff members of the Minamidaito Meteorological Observation station and all the members of Shanghai Observatory for the joint VLBI experiments.

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III. GEODETIC RESULTS OF THE EXPERIMENTS

III.3 MOVEMENT OF THE SHANGHAI STATION: IMPLICATION FOR THE TECTONICS OF EASTERN ASIA

By
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ABSTRACT

Very Long Baseline Interferometry (VLBI) data between the Shanghai station, China and other stations in the world suggest that Shanghai is moving east-southeastward by ~1 cm/year with respect to the stable interior of the Eurasian plate. This agrees with a kinematic model of crustal blocks in Central and Eastern Asia inferred from geologic and neotectonic observations(1) and the results of geophysical numerical studies of the continental collision(2). The present result gives the first space geodetic evidence supporting the hypothesis that the northward movement of the Indian subcontinent after its collision with Eurasia is partly accommodated by eastward displacements of crustal blocks in Central and Eastern Asia(3).

Keywords: VLBI, Shanghai, plate tectonics, extrusion

1. Introduction

Ocean magnetic anomaly data suggest that the Indian subcontinent has moved northward by as much as 1500 km since it started to collide with Eurasia ~40 million years ago(3). India has experienced little deformation after the collision suggesting that a certain amount of 'room' was somehow created, e.g. by north-south contraction of the Eurasian lithosphere, to enable such a movement. Molnar and Tapponnier(3) pointed out the possibility that large crustal blocks north of the collision zone have been extruded eastward one after another and interpreted large scale strike-slip faults in the Tibetan plateau as boundaries separating such crustal blocks.

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Tibet, in turn, is pushing a crustal block covering the southern part of China (South China block) eastward[4], a block sometimes depicted as the independent "China plate[5]." Several recent studies[1][2] quantitatively estimated its speed to be as fast as 1–2 cm/year, which is well detectable with a few years of space geodetic observations. The Shanghai VLBI station, located on the eastern part of the South China block, started to participate in international geodetic VLBI observations in 1988. Its directly measured instantaneous velocity will place an important constraint in modelling the tectonics of Eastern Asia.

2. Movement of Shanghai by VLBI

2.1 VLBI Experiments in China

The first geodetic VLBI experiment in China was performed in 1985 between the 26 m radio telescope at Kashima Space Research Center, Communications Research Laboratory (CRL), Japan and the 6 m antenna at the Shanghai Observatory[6]. This and a few test experiments that followed were, however, single-frequency experiments without ionospheric delay calibration data and are hence unsuitable for tectonic studies.

A new 25 m VLBI antenna at Seshan ~24 km from Shanghai and a Mark III dual frequency VLBI data acquisition terminal became operational, and in 1988 April the new Shanghai station started its activity as one of the important VLBI stations in the Crustal Dynamics Project (CDP) and Dynamics of the Solid Earth (DOSE) experiments. Shanghai has also been regularly participating in the Western Pacific VLBI Network (WPVN)[7][8] of CRL. Here we discuss its movement in terms of (1) the baseline length change between Shanghai and Kashima measured in 1988–1994, and (2) the velocity of Shanghai in the terrestrial reference frame established by the world-wide compiled VLBI data before 1992.

2.2 Kashima–Shanghai Baseline Length Changes 1988–1994

Lengths of the Shanghai–Kashima baseline measured 1988–1994 are plotted in Fig. 1. The squares are data obtained by the WPVN whose details are available in Koyama et al.[7] and Amagai et al.[8]. The circles denote CDP/DOSE data taken from Ma et al.[9] (the last two data in 1994 from the personal communication with R. Potash in 1994). The baseline data with the 26 m and the 34 m antenna at Kashima are unified to the latter by correcting for the short baseline vector between these two telescopes, which has been accurately determined by ground survey and short baseline interferometry[10].

The shortening of the baseline of ~3 cm/year (−29.7 ± 1.0 mm/year) comes partly from the displacement of Kashima. By analyzing the VLBI data 1984–1988, Heki et al.[11] estimated the horizontal movement of Kashima with respect to the Eurasian plate to be 2.6 cm/year toward N78W. They also suggested that the compressional stress field applied by the subducting Pacific plate is responsible for the east-west contraction of Japan and thereby the westward displacement of Kashima (the quantitative estimate of the contraction depends on the plate assumed for Northeast Japan; intraplate contraction of Northeast Japan becomes smaller by ~1 cm/year when the North American plate is assumed). Heki and Yoshino[12], using this displacement vector, predicted that the Kashima–Shanghai baseline may shorten by ~2 cm/year. The shortening rate in Fig. 1 is, however, significantly faster and suggests that Shanghai is not fixed on the Eurasian plate but is moving resulting in the additional shortening of ~1 cm/year.

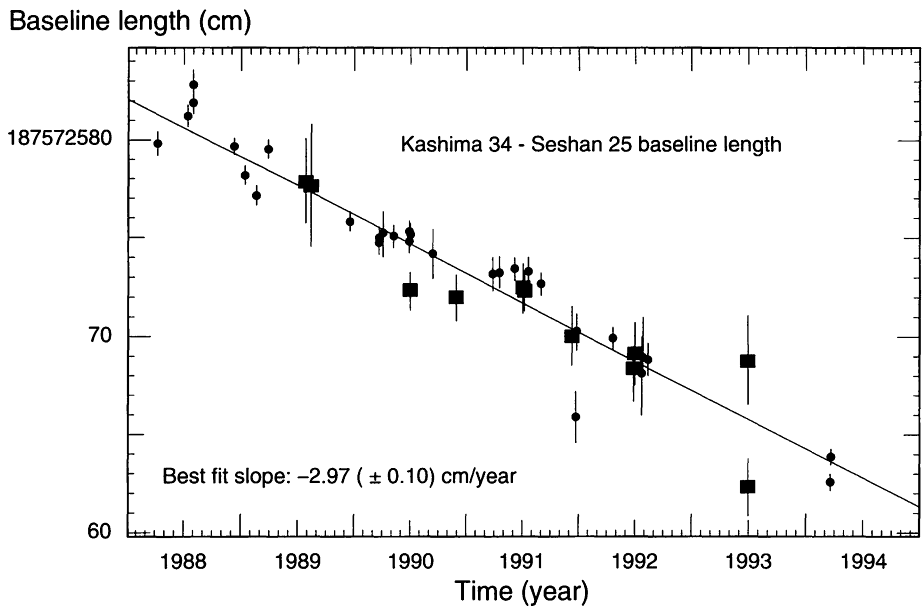

Fig. 1 The time series of the length of Kashima–Shanghai baseline. Out of 43 data, 21 are obtained with the 34 m and 22 with the 26 m radio telescopes at the Kashima station. These data are unified to those of the 34 m antenna by assuming the ~300 m baseline vector between them known, and not discriminated in this figure. 12 data were derived by the Western Pacific VLBI Network experiments (squares) and others were derived by CDP/DOSE experiments (circles). The changing rate of the baseline length estimated by weighted least-squares method is −29.7 mm/year with 1 σ formal error of 1.0 mm/year. The weighted average of the post-fit residuals is 10.7 mm.

2.3 Velocity of Shanghai up to 1992 in a Global Terrestrial Reference Frame

The Goddard Space Flight Center annually issues the results of the combined solution of the available world-wide VLBI data. The GLB907 solution[9] gives the latest terrestrial reference frame type solution, a set of site coordinates and velocities that best explains the delays observed 1979–1992. It gives a direct estimate of the velocity of Shanghai in a three dimensional space.

They achieved the minimum constraints to remove singularities in estimating site velocities by fixing the following six velocity components. Horizontal velocity of Westford (Massachusetts) and the azimuthal change of the Richmond(Florida)–Westford baseline were fixed to the no-net-rotation(nnr)-NUVEL1 plate motion model[13] predictions. The vertical movements of Westford, Richmond and Kauai (Hawaii) were fixed to zero. However, these constraints are not confirmed by other geodetic techniques, that is, a small unexpected movement of one of these stations may spuriously rotate or translate the whole kinematic reference frame. In fact, regional post-glacial isostatic rebound due to the melting of the Laurentide ice sheet is suggested to cause displacements of up to a few mm/year in the wide area of North America[14].

In this study, we perform a minor re-adjustment of the site velocities (kinematic reference frame) in the GLB907 solution following the procedure of Heki[15]; (1) selection of as many "reference" stations as possible from stable plate interiors, (2) estimation of a translation and rotation that should be added to the whole network in order to minimize their differences from the nnr-NUVEL1

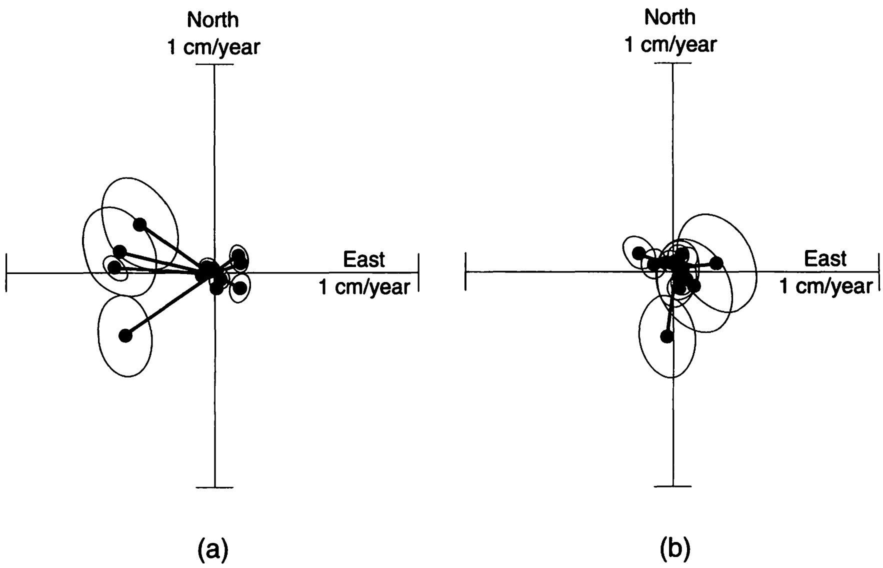

Fig. 2 Horizontal components of the residual velocities (differences between the VLBI and nnr-NUVEL1 velocities) of 14 reference stations in stable plate interiors before (a) and after (b) the re-adjustment of the kinematic reference frame. The basic VLBI data (site coordinates and velocities) are from Ma et al.[9]

predictions. Displacements of other non-reference stations (e.g. Kashima and Shanghai), with respect to the plates they are supposed to reside, are estimated together with the translation/rotation. Here we describe only a few differences from the "global frame" in Heki[15] instead of repeating the whole procedure in detail.

First we used the GLB907 solution while the GLB867 solution in the previous annual report was used in Heki[15]. Secondly, we did not use Hartbeesthoek, South Africa as a reference because it was found to lie on the boundary between the original African plate and the Somalia plate[16]. Thirdly, we minimized only the differences in the horizontal velocities while Heki[15] fitted both horizontal and vertical components (assumed zero for the vertical movement predictions). Lastly, because the full covariance matrix of the site velocities has not been available, only the within-site inter-component correlations have been used. An isotropic error, added to all the velocity vectors to make the reduced chi-square unity, was 0.52 mm/year, which is much smaller than 2.1 mm/year in Heki[15]. This is considered to be the combined effect of (1) the exclusion of Hartbeesthoek from the reference points, (2) improvement of the accuracies of the velocities of two Australian stations and (3) usage of only the horizontal velocities in determining the translation/rotation. In Fig. 2 we compare the residual horizontal velocity vectors before and after the application of the translation/rotation. The improvement of the weighted root-mean-squares (WRMS) was large in the east-west velocities; it decreased from 1.5 mm/year to 0.6 mm/year. The WRMS in the north-south component remained similar (0.6 mm/year).

This small residuals suggest that the nnr-NUVEL1 plate model (i.e. plate motion in the last few millions of years) and the VLBI measurements (i.e. plate motion in the last decade) are consistent at the level of < 1 mm/year in the plate interiors. This validates our interpretation of the movements of the "free" stations[15] estimated here, as their displacement with respect to the interior of the plates to which these stations were assumed to belong. The estimated horizontal displacements of the

Table 1 Displacements of the Shanghai, Kashima and Tsukuba VLBI stations with respect to the stable interior of the Rurasian plate

Station	Longitude	Latitude	North	East	Up
Kashima[1)]	140.67	35.95	2.8 ± 1.3	−20.8 ± 1.0	−5.1 ± 1.3
Tsukuba[1)]	140.08	36.10	2.7 ± 1.7	−20.8 ± 1.4	−5.2 ± 4.4
Shanghai[1)]	121.43	31.02	−4.5 ± 1.7	10.0 ± 1.3	−6.2 ± 3.3
Shimosato (SLR)[2)]	135.93	33.57	13.5 ± 2.1	−24.6 ± 2.1	1.3 ± 2.1

Units are mm/year and errors are 1 σ.
1) Obtained by the readjustment[(15)] of the GLB907 velocities[(9)].
2) Taken from the ITRF92[(18)].

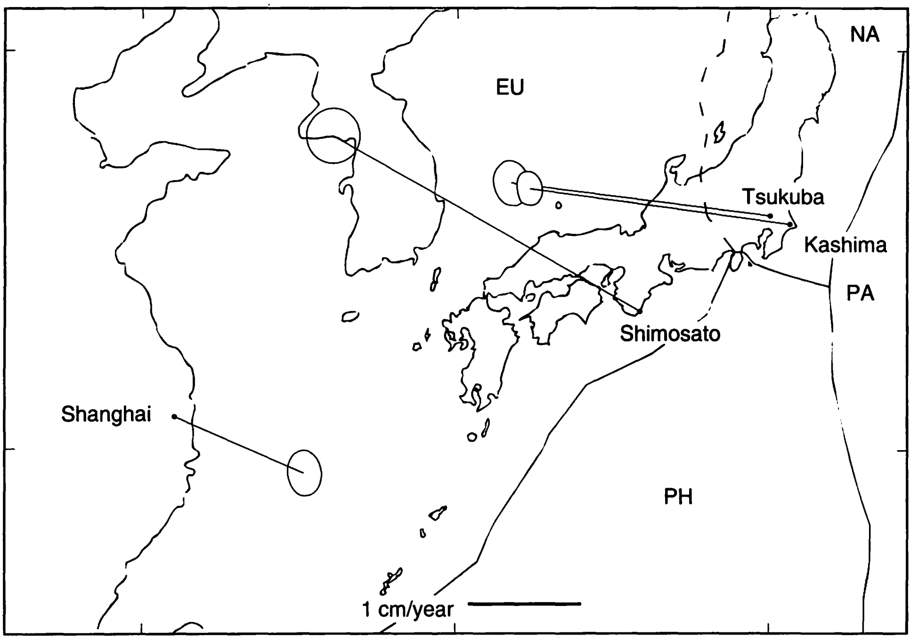

Fig. 3 The horizontal displacement vectors of the Shanghai, Kashima and Tsukuba VLBI stations with respect to the stable part of the Eurasian plate obtained in this study. Horizontal displacement of the Simosato SLR station with respect to the Eurasian plate in ITRF92[(18)] is also shown. Error ellipses are 1 σ. Components of these vectors are summarized in Table 1. PA, PH, NA and EU denote the Pacific, Philippine Sea, North American and Eurasian plates respectively. The boundary between the North American and Eurasian plate in this region is still in dispute.

Shanghai as well as Kashima and Tsukuba, with respect to the Eurasian plate, are plotted in Fig. 3 and listed in Table 1. Shanghai's movement is ~1 cm/year toward east-southeast (11.0 mm/year, N114E). As demonstrated before by Heki[(15)], such velocities are considered to be fairly stable against the selection of reference stations and plate motion models (e.g. NUVEL1a[(17)]). Shanghai also shows a fairly large subsidence (~6 mm/year) but we do not discuss this because (1) this is less than 2 σ, i.e.

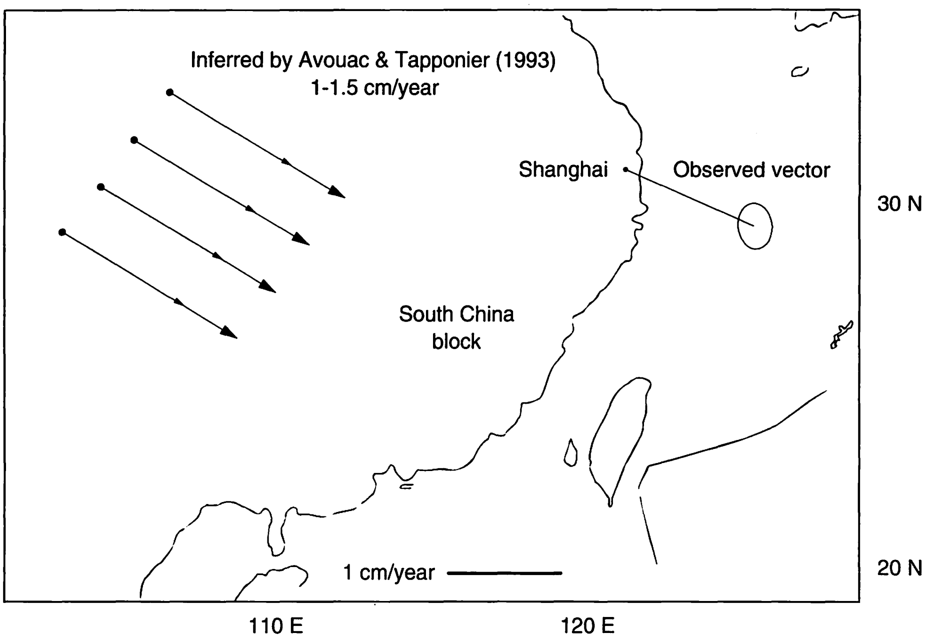

Fig. 4 The movement of Shanghai agrees well with the 'Inferred Vector,' the movement of the South China block inferred by Avouac and Tapponnier(1). It is also consistent with the numerical experiments based on a thin viscous sheet model of the lithosphere(2).

not significantly different from zero and (2) we do not have a tide gauge record near Shanghai to be compared with this.

3. Discussion and Conclusion

In spite of the controversy on the partition of the strain produced by the Indian-Asian collision between crustal thickening and eastward displacement(1)(2), there seems to be a rough agreement on the current extrusion rate of the southern China. Avouac and Tapponnier(1) estimated the velocity field of present-day deformation in Central Asia as rotations of four blocks (Siberia, Tarim, Tibet, India) on a spherical earth using geologically estimated shortening-rates across the main thrust zones and measured slip-rates along the principal strike-slip faults separating the blocks. Tibet's present-day rate of motion at its center is predicted to be ~40 mm/year northeastwards by this model. They inferred that this motion causes southeastward displacement of the eastern edge of Tibet at ~20 mm/year by a transfer mechanism involving escape and clockwise rotation of curved blocks separated by left-lateral strike-slip faults. They further suggested that this movement is attenuated to 10–15 mm/year at the western edge of the South China block across a minor thrust fault system separating Tibet from the South China block. Figure 4 shows that the observed velocity of Shanghai agrees well with this inferred velocity of the South China block.

Numerical experiments(2) based on a thin viscous sheet model of the lithosphere show that during collision the eastern boundary is smoothly displaced at a rate about a quarter of the indentation rate (i.e. the rate of the northward movement of India) with only minor variation due to geometry or rheology. The current velocity of India is ~5 cm/year and its quarter roughly agrees with the Shanghai's velocity detected by VLBI. Our study thus also gives a direct support for their numerical scheme.

Our knowledge about the present-day motion of the plates is based mainly on marine geophysical observations and so a plate motion model does not tell us much about the motions deep within the continent e.g. in Central Asia. Therefore the role of space geodetic observations is more important in such a region than in elsewhere on the Earth. A new VLBI station at Urumqi[19] in Western China, along with complementary regional GPS networks, will enable us to draw a more detailed picture of the current crustal movements in Central and Eastern Asia.

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IV. RELATED RESULTS AND ACTIVITIES IN WESTERN PACIFIC VLBI NETWORK

IV.1 THE METROPOLITAN DIAMOND CROSS EXPERIMENTS

By
Tetsuro KONDO, Jun AMAGAI, Yasuhiro KOYAMA, Kosuke HEKI, Taizoh YOSHINO, Fujinobu TAKAHASHI, Hiroo KUNIMORI, Michito IMAE, Noriyuki KURIHARA, Hitoshi KIUCHI, Shin'ichi HAMA, Yukio TAKAHASHI, Hiroshi TAKABA, Takahiro IWATA, Yuko HANADO, Akihiro KANEKO, Kuniyasu IMAMURA, Toshimichi OTSUBO, Makoto MURAKAMI*, Shigeru MATSUZAKA*, Mikio TOBITA*, Misao ISHIHARA*, Takeji KOMETANI*, Tsugunori NARITA*, and Masaru KOITABASHI*

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ABSTRACT

VLBI measurements using stations around the Tokyo metropolitan area started in 1992 in cooperation with the Geographical Survey Institute to monitor regional crustal deformation there and to establish reference points for a local geodetic survey. Repeated measurements have revealed that the 100 km baseline between two of stations (Kashima and Koganei) has been becoming shorter at a rate of about 5 mm/year due to a compressional stress field owing to the subducting Pacific plate.

Keywords: VLBI, Tokyo metropolitan area, crustal deformation

1. Introduction

Japan often has severe earthquakes. The country lies at the junction of four subterranean plates (see Fig. 1) and their relative motion is thought to be the cause of large earthquakes. A big earthquake is expected to occur at the Sagami trough in the future, and the Tokyo metropolitan area faces a similar threat. And since Tokyo has a huge concentrating population and economic activities, even a relatively small earthquake there would cause severe damage, if it occurred immediately beneath the metropolitan area. It is therefore highly desirable to develop a reliable method of predicting earthquakes to reduce the potential damage as much as possible.

A number of scientists in several countries have tried various approaches to predict the occurrence of earthquakes. The basic idea of these approaches is to try to detect a precursor of earthquake events. One such approach is electromagnetical observation, i.e., monitoring the changes occurring in the geo-magnetic field, resistive anomalies, and electric current under the ground.

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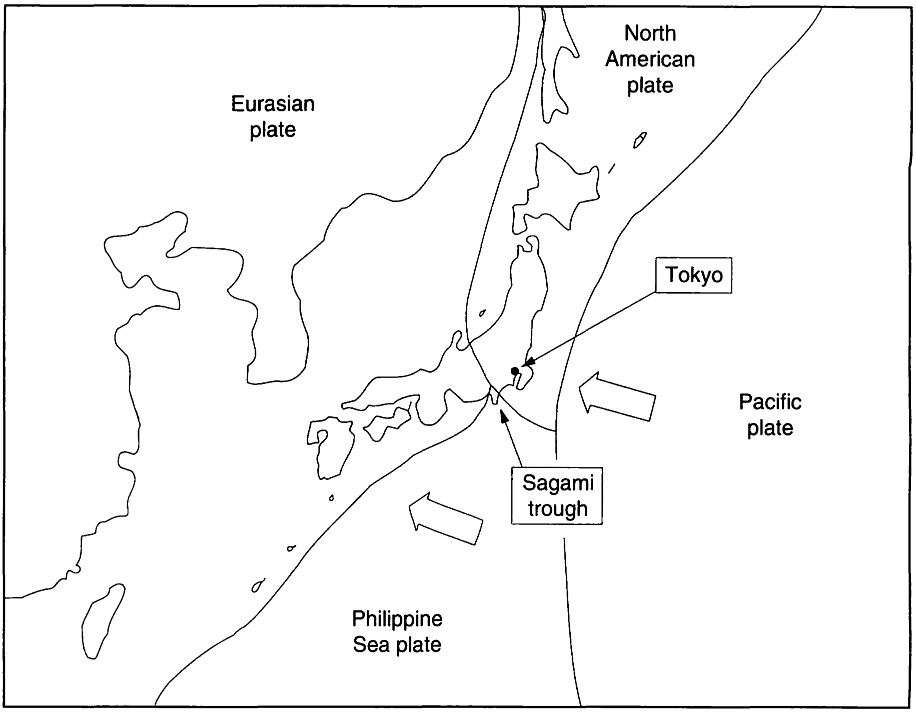

Fig. 1 The four subterranean plates around the Japanese islands. The arrows show the direction of oceanic plate motions.

Another attempt to detect a precursor is precise measurement of crustal deformation. In the former approach, observations are sometimes affected by man-made noises, and thus the latter approach is thought to be more practical for use in the metropolitan area because it is not subject to this disadvantage.

To investigate the feasibility of geodetic measurements using VLBI technique for earthquake prediction in the metropolitan area we started a series of VLBI experiments using a network surrounding the Tokyo metropolitan area in 1992. These experiments were conducted in cooperation with the Geographical Survey Institute (GSI) with financial support from the Science and Technology Agency of Japan. The main purpose of the experiments is to establish reference points in the metropolitan area and to monitor regional crustal deformation. The VLBI network consisted of three stations, Kashima, Koganei, and Tsukuba in its initial phase, and later was expanded to include Kanozan when the development of a mobile station used there was finished. The final network consisting of four stations is named the metropolitan diamond cross (MDX) after its configuration.

Prior to starting the experiments on the MDX network (or baseline), a VLBI measurement was carried out on the baseline between Kashima and Koganei in 1988. As a result, 5 years of data on the position of the Koganei is available, and this enables us to estimate the motion of Koganei relative to the Eurasian or the North American plate.

At Koganei the position has been also measured by other space geodetic techniques, i.e., satellite laser ranging (SLR) and the global positioning system (GPS). Measured positions are then connected to one another and compared. The results are described in a separate article[11] in this issue (see IV-3). In this paper, therefore, we describe only the observations and results obtained in the VLBI measurements.

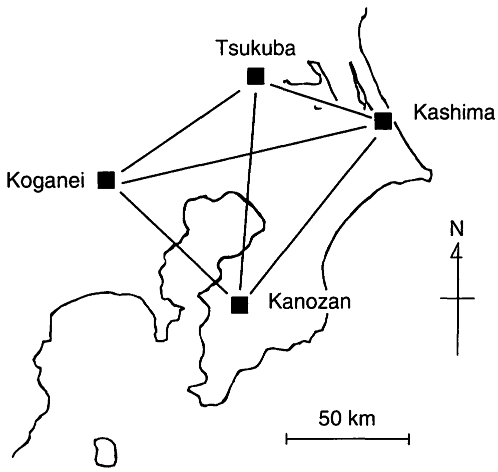

Fig. 2 Site locations and Metropolitan Diamond Cross (MDX) network

2. Metropolitan Diamond Cross Network

Figure 2 shows the locations of the VLBI stations which form the Metropolitan Diamond Cross (MDX) network surrounding the Tokyo metropolitan area, i.e., Kashima, Koganei, Tsukuba and Kanozan. All stations are located on the North American plate. The Japanese islands are thought to be in a compressional stress field owing to subducting oceanic plates, the Pacific plate and the Philippine sea plate. It is therefore suggested that any changes in baseline length or in relative station positions could be detected as a reflection of this stress field. In addition, there are many active faults reported in the Kanto plain, and thus some baselines of the MDX network are thought to cross these faults. This means that there may be a chance to detect changes occurring due to active faulting.

The key station in the MDX network is Kashima, where a large antenna (26 m or 34 m antenna) is used for the MDX session. Data processing including correlation processing is carried out there. The Koganei station has a mobile 3 m antenna with an X band receiving system[2]. Tsukuba is operated by GSI and is equipped with a 5 m antenna with dual S and X band receivers. Kanozan is also operated by GSI and has employed a mobile 2.4 m antenna with an X band receiver since 1993. Hydrogen masers are employed as a frequency standard at all stations.

3. Observations

Eight 24-hour VLBI sessions have been conducted since March, 1992 up to the present time (October, 1994) as MDX experiments. The first VLBI observation at Koganei was carried out in 1988, before the start of MDX experiments as a campaign experiment using a highly transportable VLBI station. MDX experiments at Kanozan did not begin until 1993. Table 1 shows the dates and locations of the MDX sessions and the pre-MDX session which were conducted. In conventional geodetic VLBI, both S and X band radio signals are received to calibrate the ionospheric excess delays. In contrast, only X band signals are received in the MDX sessions because Koganei and Kanozan VLBI stations are equipped only with X band receiving antennas. Thus no explicit compensation for the ionospheric delays is taken in the data reduction for MDX experiments.

Table 1 MDX experiments conducted to date

Date	Kashima		Koganei	Tsukuba		Kanozan
yy/mm/dd	26 m	34 m	3 m	5 m	2.4 m	2.4 m
88/09/20	✓		✓			
92/03/19		✓	✓	✓		
92/05/24		✓	✓	✓		
92/10/15	✓		✓		✓	
92/11/26	✓		✓			
93/05/27	✓		✓			
93/07/26		✓	✓			✓
93/07/28		✓				✓
93/08/24		✓	✓	✓		

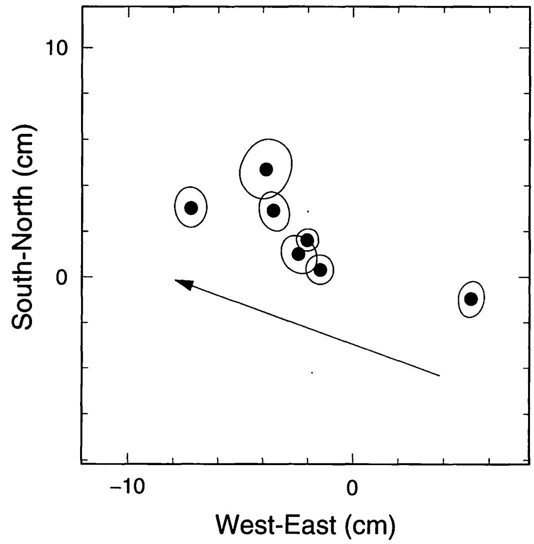

Fig. 3 Motion of Koganei relative to the Eurasian plate. The arrow indicates the least squares fitting motion over 5 years.

However, the baseline lengths between the MDX stations are considerably shorter than the scale length in the ionosphere (several hundred kilometers), so that the lack of ionospheric correction is thought to affect geodetic results only at the sub-millimeter level.

In the analysis, Kashima is treated as a reference station whose coordinate is given by the ITRF92 (IERS Terrestrial Reference Frame-92, Boucher et al., 1993)[(3)] which defines the position and velocity of stations at the epoch (1988.0).

Table 2 Position of Koganei

X (m)	−3942077.154 ± 0.006
Y (m)	3368332.197 ± 0.009
Z (m)	3701904.831 ± 0.017

Table 3 Baseline vector between Kashima 26 m and 34 m antennas

X (m)	243.019
Y (m)	109.493
Z (m)	160.607
Length (m)	311.194

Table 4 Measured baseline vector between Kashima 34 m and Kanozan

X (m)	−5901.825 ± 0.013
Y (m)	−78371.007 ± 0.011
Z (m)	63053.545 ± 0.012
Length (m)	100760.090 ± 0.005

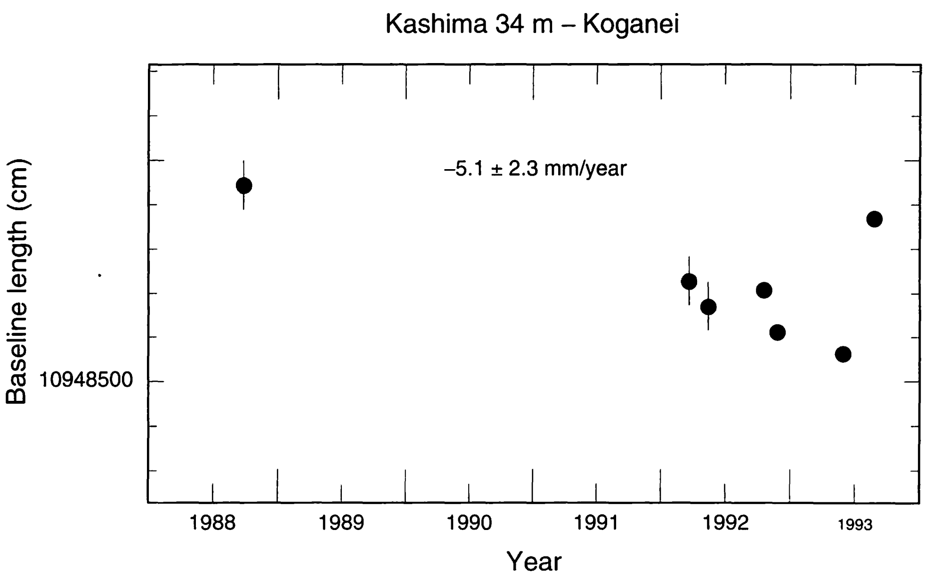

Fig. 4 Evolution of baseline length between Kashima and Koganei

4. Results

Figure 3 shows the Koganei motion against the Eurasian plate in the horizontal plane measured from 1988 on. Each ellipse represents a one sigma formal error. Estimated motion by the least squares fitting method is depicted by an arrow. The position of Koganei is summarized in Table 2 as an average the positions measured in 1992. Figure 4 shows the evolution of baseline length between Kashima and Koganei since 1988. Some measurements taken using the 26 m antenna at Kashima are converted to Kashima 34 m antenna using the relative position vector between the 26 m and 34 m antennas shown in Table 3. The measurements show that baseline length between Kashima and Koganei becomes shorter at a rate of about 5 mm/year. In the meantime, repeated measurements of the Kashima position in the international VLBI network have revealed its local motion with sub millimeter per year accuracy. Kashima is moving in the NW direction relative to both the North American and Eurasian plates at a rate of 2.4 cm/year and 1.4 cm/year, respectively, which is almost the same as the direction of the subducting Pacific plate motion (Heki et al., 1990)[(4)]. This movement is thought to be attributed to a compressional stress field caused by a subducting oceanic plate. If motion results from elastic uniform deformation over the area between the forward and backward arcs of the Japanese islands (about 300 km), strain rates of the shortening reach an order of 10^{-7}. This is fairly consistent with a shortening rate of 5 mm/year on the Kashima–Koganei baseline of about 100 km in length. The rate of change in the baseline length, however, is strongly affected by the measurements taken in 1988. It is therefore necessary to conclude that further measurements must be taken to discuss these characteristics in detail.

There is insufficient data for the Kanozan station to discuss any changes in station position or baseline length. The position measured in 1993 as a vector from the Kashima 34 m antenna is summarized in Table 4.

5. Concluding Remarks

VLBI session using stations around the Tokyo metropolitan area commenced in 1992. An MDX (Metropolitan diamond cross) network consisting of four stations, at Kashima, Koganei, Tsukuba, and Konozan, was used in carrying out the experiments. Repeated measurements on the baseline between Kashima and Koganei have revealed a shortening of its length at a rate of about 5 mm/year. This is thought to reflect the existence of a compressional stress field due to subduction of the Pacific plate. Further accumulation of position measurements for Koganei is necessary to discuss this point in detail because the results shown here are strongly affected by a pre-MDX measurement made in 1988. Moreover, Kanozan was not installed in the network until 1993, and thus further measurements are needed to more clearly determine the nature of strain in the MDX network.

6. Acknowledgments

The metropolitan diamond cross (MDX) experiments were conducted in cooperation with the Geographical Survey Institute with financial support from the Science and Technology Agency (STA) of Japan. The development of 2.4 m mobile VLBI station was financially supported by the Environment Agency.

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IV. RELATED RESULTS AND ACTIVITIES IN WESTERN PACIFIC VLBI NETWORK

IV.2 SHORT REPORT OF THE EXPERIMENTS WITH THE URUMQI VLBI STATION, WESTERN CHINA

By
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(Received on November 21, 1994)

ABSTRACT

Very Long Baseline Interferometry (VLBI) experiments were carried out between Japan and China using a newly constructed VLBI station at Urumqi in western China which was equipped with the data acquisition system transported from Communications Research Laboratory (CRL). The first VLBI fringe of the Urumqi station was detected, and the position of the 25 m antenna at Urumqi was derived within an error of several centimeters, which indicates that the Urumqi station is established as a unique VLBI station on the central part of the Eurasian Plate.

1. Introduction

Urumqi in western China is located on the central part of the Eurasian Plate which is conjectured to be a stable part against the plate deformation provoked by the conflict between the Indian Plate and the Eurasian Plate at the Himalayas(1). On the other hand, Shanghai is thought to be on the South China block of the Eurasian Plate(1), where the east-southeastward displacement caused by the deformation of the plate had been detected by the experiments with the Western Pacific VLBI Network(2). Consequently, Urumqi is a candidate remarkable point as a geodetic standard of the stable interior of the Eurasian Plate which is effective for the elucidation of the plate deformation.

A 25 m antenna for geodetic VLBI and radio astronomy observations was constructed at Urumqi Astronomical Observatory of the Chinese Academy of Sciences (CAS) in 1992(3). We executed the first international geodetic VLBI experiments with the Urumqi station for the purposes of the establishment of the VLBI system and the precise positioning of the station in 1994. Because the VLBI data acquisition system had not been equipped by the Chinese side yet, it was transported from CRL for temporary use.

[1]Urumqi Astronomical Observatory, The Chinese Academy of Sciences
[2]Shanghai Observatory, The Chinese Academy of Sciences

Table 1 Properties for the experiments

Properties in common with each station			
Receiving frequency band	S/X band		
Mode of data acquisition	2 MHz × 14 ch		
Frequency standard	Hydrogen maser		
Specific properties for each station			
Station	**Kashima**	**Urumqi**	**Shanghai**
Antenna diameter	34 m	25 m	25 m
T_{sys} (S band)	71 K	160 K	140 K
T_{sys} (X band)	52 K	100 K	120 K
Efficiency (S band)	65%	46%	50%
Efficiency (X band)	68%	50%	60%
Data acquisition system	K-4	K-4	MK-III

2. Experiments

Geodetic VLBI experiments were executed using the 34 m antenna of Kashima Space Research Center of CRL, the 25 m antenna of Urumqi Astronomical Observatory of CAS, and the 25 m antenna of Shanghai Observatory of CAS. The K-4 type VLBI data acquisition system[(4)(5)], including the video convertor, the local oscillator, the input interface, and the data recorder, was transported from CRL to the Urumqi station before the experiments. A phase calibrator was also transported from CRL and equipped to the antenna at Urumqi.

Two sessions of a 24-hour observation were made from 7:00 UT on February 28 and 7:00 UT on March 2, 1994. 23 radio continuum sources toward extragalactic quasars were observed in S band at 2 GHz and X band at 8 GHz simultaneously. The VLBI data were recorded with 14 channels of 2 MHz by the K-4 type VLBI data acquisition systems at Kashima and Urumqi, and Mk-III type system at Shanghai, respectively. Frequency standard signals were generated by hydrogen masers at each station. These observational properties are summarized in Table 1. The signal of the phase calibrator at Urumqi, however, could not be optimized to the antenna system, and the hydrogen maser at Shanghai were unstable during the experiments. The correlation processing using the K-3 type VLBI correlator[(6)] and the baseline analysis were performed at Kashima from March to April 1994.

3. Results and Discussion

VLBI fringes including the first fringe by the Urumqi station was successfully detected for all the baselines in conjunction with Kashima, Urumqi and Shanghai on both S band and X band in the correlation processing. Because of the inferior quality of the phase calibrator signal at Urumqi, we assumed, in the bandwidth synthesis processing, that the phases for each scan and the relative phases for each channel at Urumqi have constant values as those obtained from the scans with large signal to noise ratio during the observations. Results of the obtained position for the Urumqi station are summarized in Table 2 with ITRF92 coordinates[(7)]. The distance between Kashima and Urumqi antenna is estimated to be 4,484,257.466 ± 0.026 m. Figure 1 also shows the obtained baseline length between Kashima and Urumqi and the distribution of the VLBI stations. Thick solid lines and broken

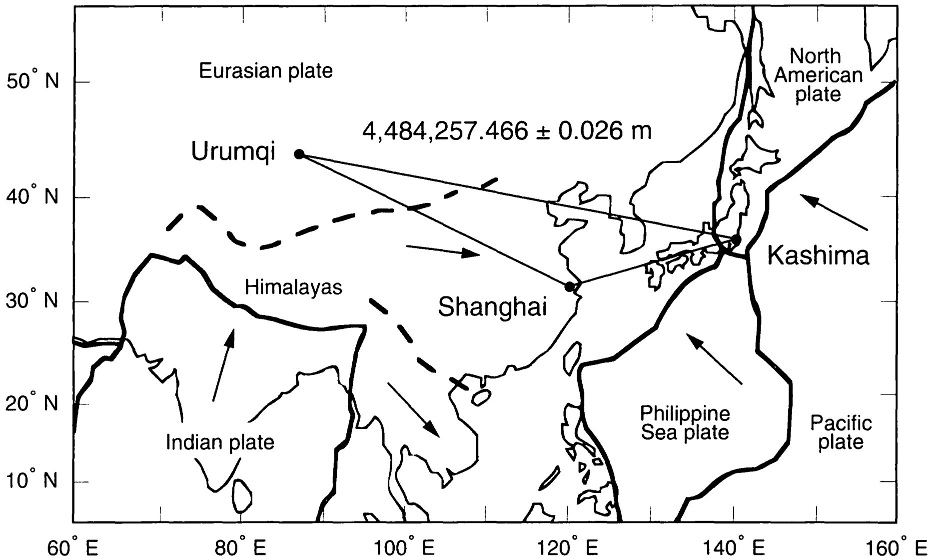

Fig. 1 The distribution of the VLBI stations and the baseline length between Kashima and Urumqi obtained by the VLBI experiment. Thick solid lines and broken lines denote the boundaries of the plates and the South China block, respectively, and arrows denote the directions of the plate motion.

Table 2 Results for Urumqi Station

Position of Urumqi by ITRF92 coordinates
X = 228,310.845 ± 0.038 m
Y = 4,631,922.768 ± 0.065 m
Z = 4,367,063.951 ± 0.037 m
Base line length between Kashima and Urumqi
L = 4,484,257.466 ± 0.026 m

lines in Fig. 1 denote the boundaries of the plates and the South China block, respectively, and arrows denote the directions of the plate motion, which indicate that Urumqi is located on the stable interior of the Eurasian Plate.

The error on the order of several centimeters derived from our VLBI experiments is smaller by about four figures than that of several hundred meters measured by GPS at Urumqi. It is, however, larger than those of typical geodetic VLBI measurements, which is thought to be due to the inferior quality of the phase calibrator signal at Urumqi. The averaged loss of correlated amplitudes caused by phase synthesis processing is about 5% for the baseline between Kashima and Urumqi, which indicates that the frequency standard signal at Urumqi had enough stability. These results show that though the optimization of the phase calibrator signal is necessary for the improvement of the system, the Urumqi station is established as a geodetic VLBI station.

4. Conclusion

The first international geodetic VLBI experiments were executed between Urumqi, Kashima, and Shanghai, using the K-4 VLBI data acquisition system transported from CRL to Urumqi. The first VLBI fringe of the Urumqi station has been detected, and the position of the 25 m antenna at Urumqi was estimated within an error of several centimeters. Though the error of the derived position at Urumqi is larger than those in conventional geodetic VLBI experiments, we can conclude that the Urumqi VLBI station is established to be of a unique one on the central part of the Eurasian Plate.

5. Acknowledgement

The authors are grateful to all the members of VLBI groups at Kashima Space Research Center, Urumqi Astronomical Observatory, and Shanghai Observatory who gave us helpful supports and comments.

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IV. RELATED RESULTS AND ACTIVITIES IN WESTERN PACIFIC VLBI NETWORK

IV.3 COLLOCATION AND LOCAL-TIE OF SPACE GEODETIC TECHNIQUES, VLBI, SLR, AND GPS IN CRL, TOKYO

By
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(Received on November 21, 1994)

ABSTRACT

The global position of the station in the Communications Research Laboratory (CRL), Tokyo was determined independently by means of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) techniques with a precision of several centimeters. Local-tie survey among ground markers and points on which the techniques are referenced in position have also been done. The coordinates from three results from various source of analysis are consistent within 7 cm peak to peak. The difference may include uncertainty in local-tie measurement (3 cm in maximum) and in coordinates transformation in a comparison process (2.5 cm in mean) as well as in the observations themselves especially in vertical component.

Keywords: VLBI, SLR, GPS, collocation, IERS

1. Introduction

Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) are the major space geodetic techniques for determining the relative station position over intercontinental distance with centimeter-level precision. Since the two techniques are independent in their observation principles, it is of interest to compare results from them to evaluate the accuracy of the measurements when they are collocated in the same place. Global Positioning System (GPS), another precise geodetic technique widely used for monitoring a local deformation, is also utilized as a means of local-tie between other space techniques in a collocation process.

There are three major stages in a collocation process to evaluate uncertainty of the station position of interest. The first is the observation and data processing by each technique. The uncertainty of the station position should be expressed by an internal error based on the observation and analysis model. The second, local-tie between each technique should be performed precisely enough within the internal observation error. The distance between the reference point of each

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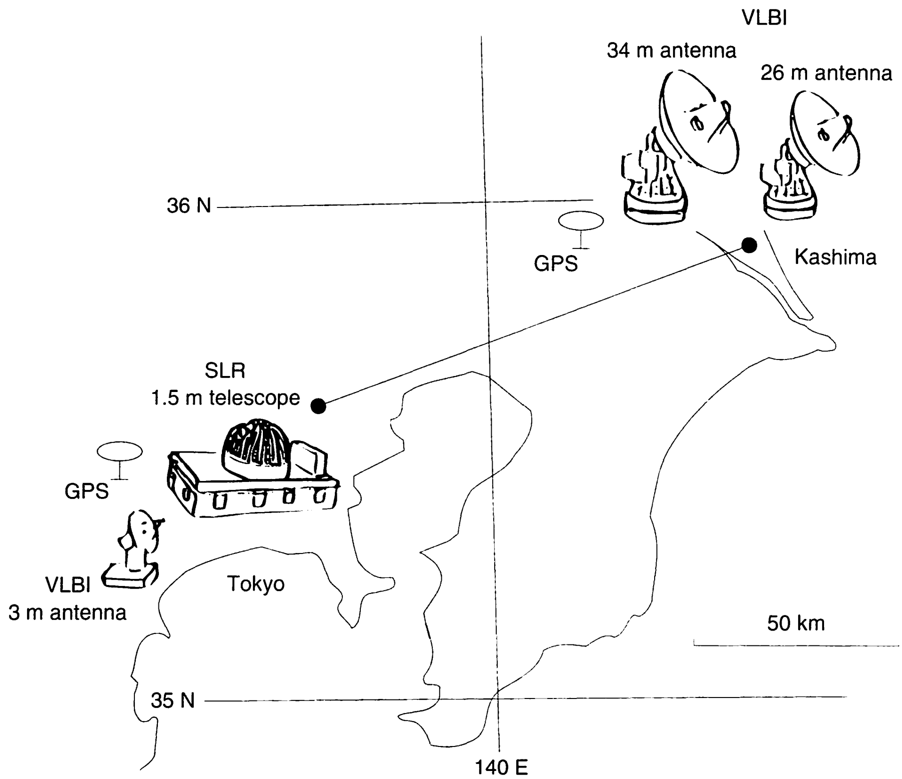

Fig. 1 The location of each technique in Tokyo and Kashima

techniques generally ranges from a few meters to several tens of km, and the goal of local survey accuracy within 1 cm would not be easy to get, especially in case that the reference point is covered by telescope or antenna structures. Finally in the third process, the coordinates transformation may be required depending on the difference of definition of each coordinate system. The transformation should be made in attention to the observation epoch and adopted plate motion model . The activities of collocation to establish an unified global coordinates have been organized by the International Earth Rotation Service (IERS) and the results have been annually reported as the IERS Terrestrial Reference Frame (ITRF)(1).

The Communications Research Laboratory (CRL) has developed geodetic VLBI system for the last two decades. It has performed more than seventy international and domestic VLBI experiments using 26 m and 34 m antennae at the Kashima Space Research Center, Ibaraki (KASHIMA), and also at Koganei, Tokyo using a 3 m mobile antenna(2). Kashima has been established as one of the major sites in a global terrestrial reference frame(1). Tokyo SLR station in Koganei (CRLLAS), one of the facilities in the Space Optical Communication Ground Station, started observation in February 1990 and obtained more than 350 passes in total for major geodetic satellites up to the height of 20,000 km(3). Although the system is not in operation routinely but is acting as an engineering test bed for the research and development, the global position of the station was determined by CRL and IERS independently. The Tokyo SLR station has been collocated with mobile VLBI antenna since 1988 and has been connected to the Kashima VLBI station. The conventional local-tie surveys in Kashima and Koganei have been done, mainly by Geographical Survey Institute (GSI) using both the

Table 1 The station coordinates of Tokyo SLR station, Kashima 26 m and Kashima 34 m antenna in ITRF92[1] (Epoch: 1988.0, Unit: meter)

	X	Y	Z
Tokyo SLR (7308)	−3,942,020.077 +/−0.116	3,368,097.548 +/−0.112	3,702,191.136 +/−0.138
Kashima 26 m (1856)	−3,997,892.252 +/−0.007	3,276,581.252 +/−0.006	3,724,118.349 +/−0.010
Kashima 34 m (1857)	−3,997,649.233 +/−0.008	3,276,690.751 +/−0.007	3,724,278.957 +/−0.011

Table 2 The baseline vectors between Kashima 26 m and Koganei 3 m antenna obtained by VLBI (Epoch: 1988.0 and 1990.0, Unit: meter)

	X	Y	Z	Epoch
Kashima 26 m	55,814.886	91,750.862	−22,213.418	1988.0
Koganei 3 m	55,814.908 +/−0.020	91,750.843 +/−0.015	−22,213.436 +/−0.017	1990.0

Table 3 Coordinates of CRLLAS (Tokyo) in CSR91L01 geocentric coordinate system (Epoch 1983.0, Plate Motion Model: AM1-2, Unit: meter)

X	Y	Z
−3942019.882 +/−0.048	3368097.932 +/−0.056	3702191.126 +/−0.080

Electronic Distance Meter (EDM) and GPS methods. The GPS receivers have been also used for baseline determination between KASHIMA and CRLLAS. The location of each technique on the map is shown in Fig. 1.

2. Experiments and Data Analysis

2.1 VLBI

The Koganei 3 m mobile antenna was established in September 1988, conducting the first VLBI experiment with the Kashima 26 m antenna. It was then moved to a remote island and returned in 1992 to perform further experiments with a 26 m and a newly built 34 m antenna switching over in Kashima during the Metropolitan Diamond Cross (MDX) program[4][5]. The data sets used in our analysis are those from seven experiments during the period from September 1988 to July 1993.

We fixed the position of the Kashima 34 m antenna given by ITRF92[2] (See Table 1) where the relative coordinates between the 26 m and 34 m antennae were determined by GLB867[6]. The physical model depended on the software CALC version 7[7]. Atmospheric correction towards the zenith was done in offset and slope every 6 hours by applying a mapping function NMF[8]. Clock

Table 4 The geodetic reference points and ground markers in Koganei, Tokyo

No.	Name	Mnem-onic	Type	Status	Description	Year set	North	East	Height
1	SLR AXIS	S	AXIS	Permanent[1]	1.5 m telescope Az-El intersection point	1988–		See text	
2	VLBI AXIS '88	V88	AXIS	Settable[3]	1988 Sep. occupation of 3 m VLBI antenna Az-El intersection point	1988.9–10		See text	
3	VLBI AXIS '92	V	AXIS	Settable[3]	1992 Mar.-occupation of 3 m VLBI antenna Az-El intersection point	1992.3–		See text	
4	TERY_E	T	POLE	Permanent[1]	Terrestrial target on the building eastward from telescope	1989–	0.000	0.000	0.000
5	TERY_W	TW	POLE	Permanent[1]	Terrestrial target on the ground westward from telescope	1989–	14.902	−100.358	−8.068
6	PRESTAR	P	MRK	Tentative alive[4]	Marker on the roof top of the Maser building (used as PRESTAR GPS receiver)	1989–	−356.883	−135.925	−4.631
7	GSI plate	G	PLAT-E	Permanent[1]	The plate GSI set on the no. 3 building in 1975	1975–	−381.497	−54.552	3.343
8	AOA	A	ANT	Settable[3]	AOA receiver for GPS time comparison set on the pole on the no. 3 building	1989–		–	
9	SLR NE	SNE	GRD	Permanent[1]	Ground base at optical center north east in 1992	1992–	66.556	18.623	−10.851
10	SLR SE	SSE	GRD	Permanent[1]	Ground base optical center southeast in 1992	1992–	−40.658	5.398	−11.759
11	SLR SW	SSW	GRD	Permanent[1]	Ground base optical center southwest in 1992	1992–	−31.319	−64.864	−10.353
12	TEMP NE	–	TMP	Tentative obsolete[5]	Ground marker at optical center northeast in 1990	1990–90		–	
13	TEMP N1	–	TMP	Tentative obsolete[5]	Transit ground marker at optical center north in 1990	1990–90		–	

1) The point is (would be) permanent
2) It is used for tentative azimuth reference
3) Position would be changed at every set up, but not changed during in operation
4) The point is tentative but still be used as survey
5) The point is tentative and already obsolete

Table 4 The geodetic reference points and ground markers in Koganei, Tokyo—continued

No.	Name	Mnem-onic	Type	Status	Description	Year set	North	East	Height
14	TEMP N2	–	TMP	Tentative obsolete[5)]	Transit ground marker at optical center north in 1992	1992–92		–	
15	TEMP SE1	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southeast in 1989	1989–89		–	
16	TEMP SE2	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southeast in 1990	1990–90		–	
17	TEMP SW1	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southwest in 1989	1989–89		–	
18	TEMP SW2	–	TMP	Tentative obsolete[5)]	Ground marker at optical center southwest in 1990	1990–90		–	
19	VLBI N	VN	GRD	Permanent[1)]	Ground base at 3 m antenna north in 1992	1992–	−319.802	−157.142	−11.423
20	VLBI S	VS	GRD	Permanent[1)]	Ground base at 3 m antenna south in 1992	1992–	−361.970	−153.047	−11.224
21	TEMP VLBI	–	MRK	Tentative alive[4)]	Marker on the 3 m antenna base	1990–	−345.582	−151.732	−10.969
22	TEMP 4B1	–	TEMP	Tentative obsolete[5)]	Transit marker on the top of no. 4 building in 1989	1989–89		–	
23	TEMP 4B2	–	TEMP	Tentative obsolete[5)]	Transit marker on the top of no. 4 building in 1990	1990–90		–	
24	NTT	–	AZM	Azimuth ref[2)]	The lightning rod on the NTT tower for the azimuth reference at point P	1988–		–	
25	TANASHI	–	AZM	Azimuth ref[2)]	The lightning rod on the Tanashi tower for the azimuth reference at point T	1988–		–	
26	No. 3 build.	–	AZM	Tentative azm. ref.	The lightning rod on the no. 3 building of CRL	1988–		–	

1) The point is (would be) permanent
2) It is used for tentative azimuth reference
3) Position would be changed at every set up, but not changed during in operation
4) The point is tentative but still be used as survey
5) The point is tentative and already obsolete

Table 4 The geodetic reference points and ground markers in Koganei, Tokyo—continued

No.	Name	Mne-monic	Type	Status	Description	Year set	North	East	Height
27	KSP build.	KS1	POLE	Permanent[1]	Pole for GPS/geodetic measurement on the KSP building	1994–	30.468	−102.107	0.131
28	KSP NE	KS2	POLE	Permanent[1]	Pole for GPS/geodetic measurement northeast around 11 m antenna	1994–	75.403	−63.981	−8.348
29	KSP N	KS3	GRD	Permanent[1]	Ground base in north of 11 m antenna	1994–	85.609	−106.297	−9.843
30	KSP W	KS4	GRD	Permanent[1]	Ground base in west of 11 m antenna	1994–	49.144	−122.330	−9.981
31	GSI POLE	GP1	POLE	Permanent[1]	5 m tall pole for GPS measurement for GSI	1994–	16.920	−113.265	−3.860
32	TEMP P	–	MRK	Tentative alive[4]	Marker 3 m off north of PRESTAR point	1992–		–	
33	TEMP T	–	MRK	Tentative alive[4]	Marker 2 m off north of Tery_E point	1992–		–	
34	AZM PLATE	AZM	GRD	Permanent[1]	Ground base for azimuth reference at north-east of ground field	1995–		The local coordinate origin on no. 4.	

1) The point is (would be) permanent
2) It is used for tentative azimuth reference
3) Position would be changed at every set up, but not changed during in operation
4) The point is tentative but still be used as survey
5) The point is tentative and already obsolete

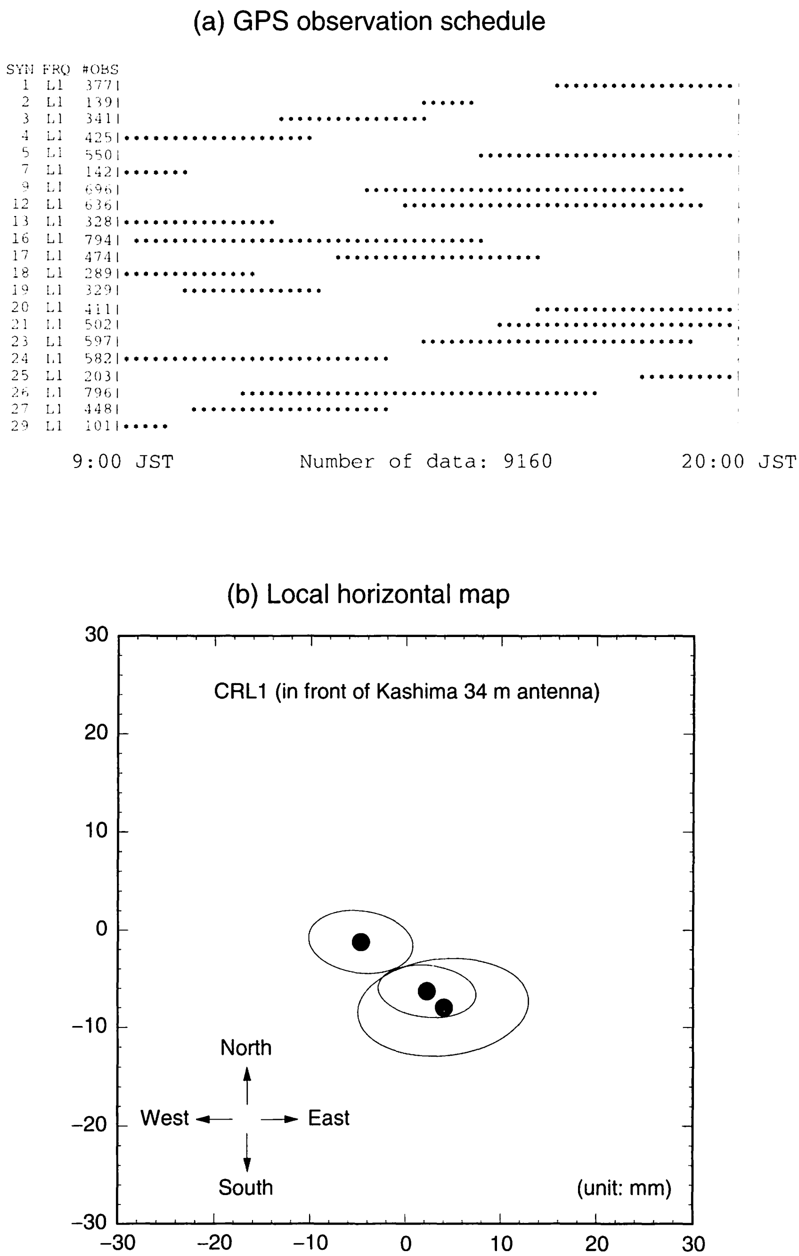

Fig. 2 (a) The schedule of GPS observation and (b) the example of horizontal repeatability in Kashima GPS site

offset and rate was estimated every 2 hours. No ionospheric correction was made since 3 m portable station was capable of receiving only X band frequency. The Kashima-Koganei baseline vectors in epoch 1988.0 and 1990.0 derived from VLBI are listed in Table 2.

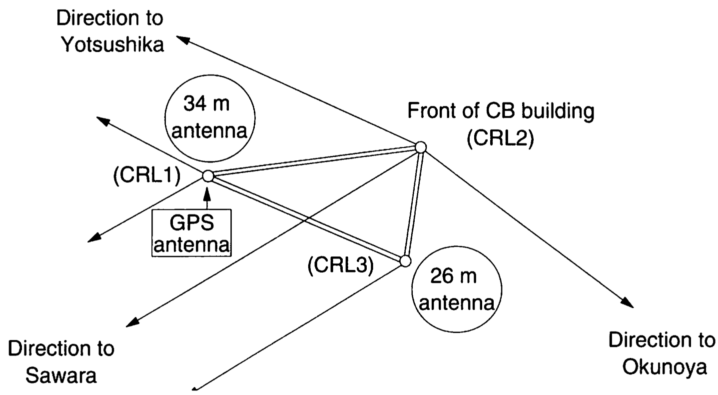

Fig. 3 The schematic survey map in Kashima (CRL1, 2 and 3 are the ground markers)

2.2 SLR

The data sets used in the analysis were 19,554 LAGEOS passes in total (including 38 passes in CRLLAS) obtained by 35 SLR tracking stations during a period from September to November 1990 when ETALON tracking campaign was organized in the global SLR network. Data analysis has been made using University of Texas Orbit Processor and Application (UTOPIA) software[9]. The TEG50 geopotential model and CSR Earth Orientation Parameter were used in the analysis. The global position of the Tokyo SLR station in CSR91L01 coordinate system is listed in Table 3. The coordinates are based upon the reference epoch 1983.0 being evolved by plate motion model AM1-2.

The same data were also analyzed in the ITRF92 reference frame by the IERS. The results are reported in ITRF92 which has 11 to 14 cm formal error in each component in Table 1. We have found that it is due to the range bias of 30 cm included in the initial released data and to be corrected in the later release.

2.3 GPS

The CRL owns three commercial geodetic receivers (Ashtech XII-P), capable of C/A code, L1/L2 carrier, and P-code measurement. We have participated in the "GPS JAPAN '93" campaign locating them in the vicinity of the Koganei SLR telescope building, the Kashima 34 m, and the Inubo Radio Observatory, respectively. The schedule and the position repeatability obtained during the campaign is shown in Fig. 2.

Data analysis was made by using an on-site modification version of the Bernese GPS software ver. 3.4 running on a HP workstation. In the analysis, we used the broadcast orbital elements and Kashima coordinates fixed as the ITRF92 site. A cyclic slip elimination was done manually and ionospheric excess path was corrected by L1/L2 frequency.

3. Local-Tie Survey

The origin of VLBI-antenna/SLR-telescope and ground marker has been surveyed by the CRL and GSI, respectively where the origin is defined as at the intersection of two orthogonal rotating axes.

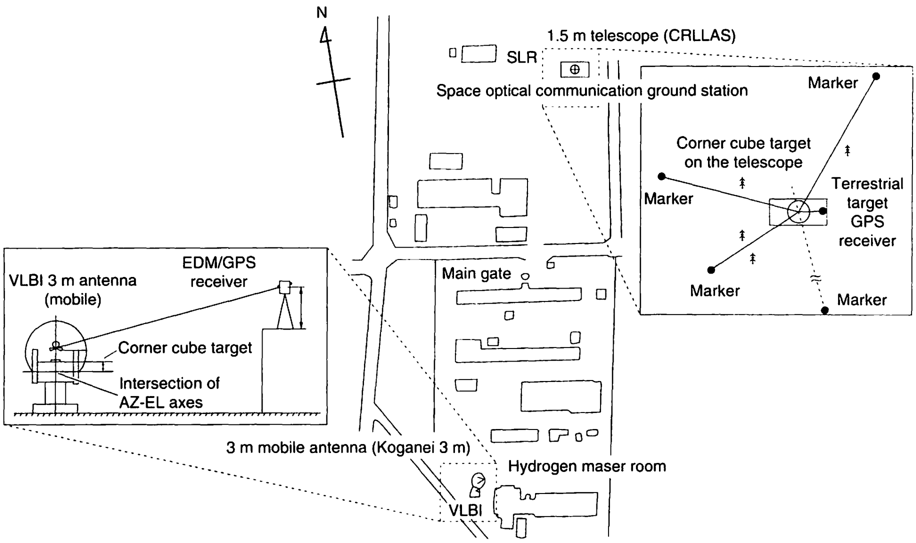

Fig. 4 The location of SLR, VLBI and GPS in CRL Koganei, Tokyo

In the Kashima Research Center, there are three major geodetic markers and measurements of the relative position with respect to 26 m and 34 m VLBI antennae have been done by GSI[(10)]. The schematic survey map is shown in Fig. 3.

In Koganei, such surveys with respect to 3 m VLBI antenna and 1.5 m SLR telescope have been done many times since 1988 by CRL and GSI. Figure 4 shows the map of local tie in Koganei and Table 4 lists all the geodetic reference points and ground markers in Koganei. The SLR telescope is located 500 north of the VLBI antenna. We made local-tie measurement between them by GPS receiver and by conventional EDM method. The major local-tie vectors between reference points are listed in Table 5. It should be pointed out that the discrepancy between the CRL and GSI results are 3 cm peak to peak and should be examined by further survey.

4. Comparison

4.1 Comparison between VLBI and SLR: Results of Transformation from ITRF92 to CSR91L01 Coordinates

Using the position of Kashima by ITRF92 and position of CRLLAS by CSR91L01 described in 2.2, we made a coordinate adjustment. Figure 5 illustrates the comparison process between VLBI and SLR coordinates each of which has different definition. It aims to minimize the error for the difference of the plate motion model used in each solution. First, we prepare the two sets of coordinates for collocation sites, one set from ITRF92 and another for CSR91L01. Second, the epochs of station position for both system are moved to the common observation epoch (1990.0) by the adopted plate motion model namely nnr-NUVEL-1 for ITRF92 and AM1-2 for CSR91L01. Third, adding the local-tie information given by J. Ray et al. 1991[(11)], the transformation matrix (offset, rotation and scale) between two systems is calculated by least square method. Then we apply

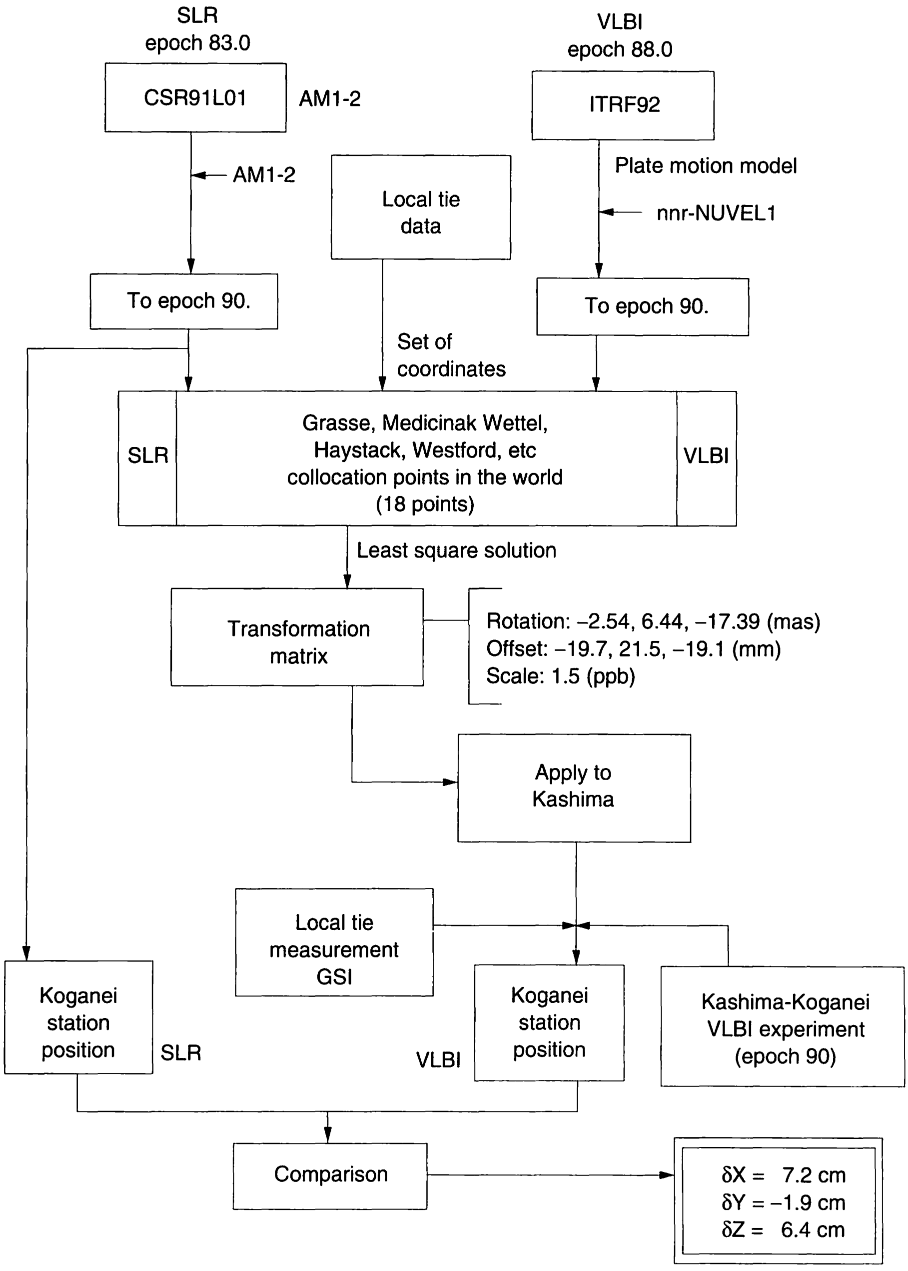

Fig. 5 Flow diagram of comparison process between SLR and VLBI in custom coordinates

it to the Kashima station to produce the position equivalent to one by CSR91L01 at epoch of 1990.0. Finally, Kashima-Koganei baseline vector in epoch 1990.0 and local-tie vector in Koganei are added for final comparison. Note the effect of the transformation for Kashima-Koganei and local-tie vectors

Table 5 The relative vectors for local-tie between major reference points in geocentric coordinate system (Unit: meter)

Vector	X	Y	Z
Kashima 34 m to Kashima 26 m	−243.019	−109.493	−160.607
Kashima-GPS to Kashima 34 m	−39.895	−64.923	44.260
Koganei 3 m to CRLLAS (SLR)	57.220	−234.522	286.214
CRLLAS (SLR) to Koganei-GPS	−8.771	−7.458	−1.030

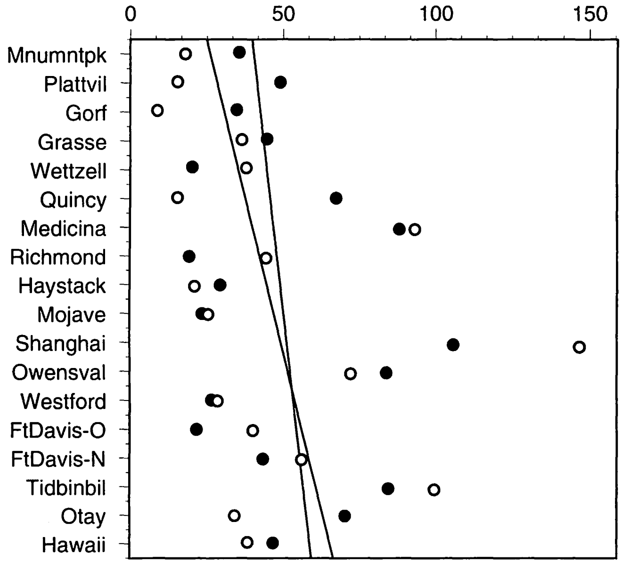

Fig. 6 Residuals after adjustment of VLBI and SLR coordinates for the collocation sites. (Black dots: Results from custom adjustment in this paper, White dots: Results from J. Ray et al.[11], Unit: mm)

are negligible here. The difference of coordinates between SLR and VLBI at Tokyo SLR station are 7.2, −1.9 and 6.4 cm, respectively, in geocentric component.

The result from straightforward comparison with ITRF92 CRLLAS coordinates versus ITRF92 Kashima (using number from Table 1, Table 2 and Table 5) are 6.9, −4.4 and −0.9 cm respectively which shows the comparable difference with the results given above.

Figure 6 shows the residuals after adjustment of VLBI and SLR coordinates. The black dots are from our results and the open dots come from J. Ray et al. 1991[11]. The stations are arranged by the distance between the VLBI and SLR sites in ascending order. The straight lines, which all the data fits, explain a dependence of distance of the two techniques. Weighted rms of residuals are 2.5 cm in both analyses. However, some stations (Medicina, Shanghai, OwensVally, and Tidbinbilla) have large residuals and must be studied more carefully in the local-tie measurement.

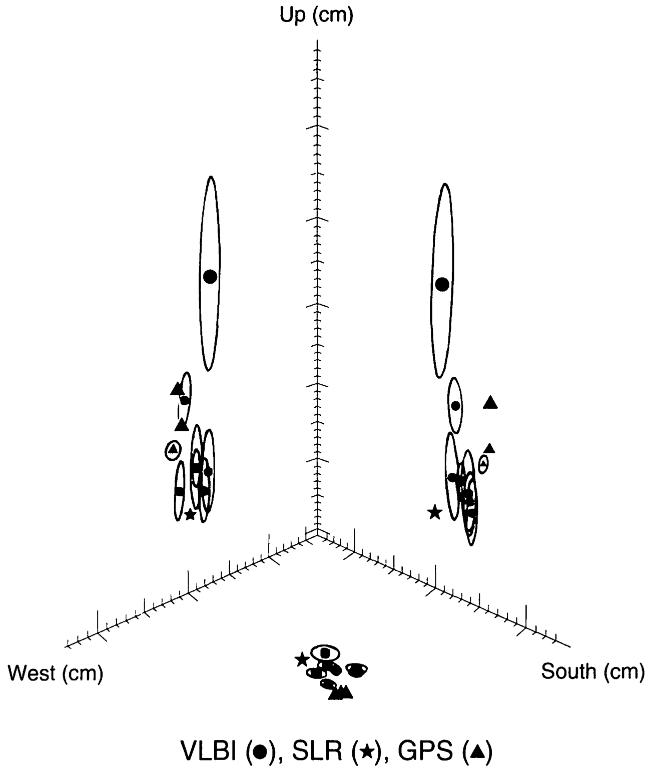

Fig. 7 The coordinates projection to local geodetic coordinate by VLBI, SLR and GPS. Error ellipsoids shows 1 sigma for VLBI, 3 sigma for GPS. No ellipsoid for SLR plot here due to large formal error in ITRF92.

4.2 Results of IERS Coordinates Comparison using ITRF92 Coordinates (3 Techniques Comparison)

Using ITRF92 coordinates at Kashima and Koganei and local-tie information all consistent in Epoch 88.0, we obtained the comparison of VLBI, SLR and GPS coordinates. Figure 7 shows the Koganei 1.5 m telescope position in a local coordinates determined by three techniques. The error ellipses are given by each technique except SLR where ITRF92 solution has a large error. The scatters of 20 cm peak to peak in vertical component are seen in VLBI possibly caused by non-ionospheric correction in VLBI. The repeatability of GPS observation is as good as 1 cm in horizontal and 3 cm in vertical, but the results might include a systematic error due to atmosphere because the campaign was performed within a short time. The mean of VLBI position, if we exclude point which has the largest error ellipsoid, will coincide with GPS and SLR within 5 cm.

The difference would include errors in local-tie measurement and coordinates transformation in a comparison process as well as errors in SLR/VLBI observation themselves.

5. Conclusion

The activities of collocation study in CRL are presented. The coordinates from three results from various source of analysis are coincident to within 7 cm peak to peak. The difference may include uncertainties in local-tie measurements (3 cm in maximum) and in coordinates transformation in a comparison process (2.5 cm in mean) as well as in the observations themselves, especially in vertical component.

To improve collocation accuracy, we should increase the number of SLR observations in Tokyo to put the range bias correctly and should increase the VLBI observations in Tokyo to determine the relative station motion. We should also improve the accuracy of local-tie survey not only for Tokyo but for the other collocation points in the world. They should contribute to the reference frame accuracy better than 1 cm.

6. Acknowledgment

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IV. RELATED RESULTS AND ACTIVITIES IN WESTERN PACIFIC VLBI NETWORK

IV.4 RADIO ASTRONOMY WITH THE KASHIMA 34 M ANTENNA

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(Received on November 21, 1994)

ABSTRACT

CRL's 34 m antenna at Kashima which is equipped with low noise receivers which operate from 1.5 GHz to 43 GHz, covers most of the radio astronomical bands in this frequency range. The antenna has extremely accurate surface panels and is highly efficient even on the millimeter wavelength. Many kinds of single dish observations and radio astronomical VLBI observations have been performed. Domestic VLBI experiments between the Kashima 34 m and the Nobeyama 45 m antennas are called KNIFE and are highly sensitive on the short centimeter and millimeter wavelengths. VLBI experiments between the Usuda 64 m and the Kashima 34 m antennas were called UKAI and are highly sensitive on the 2 GHz and 8 GHz bands. This paper reviews published work on radio astronomy by using data obtained from the 34 m antenna at Kashima. The results of observations of astronomical masers, extragalactic radio continuum sources, pulsars, and interplanetary scintillation (IPS) observations are presented.

Keywords: radio astronomy, antenna, VLBI, time and space

1. Introduction

The Kashima 34 m antenna (Fig. 1) was built in 1988 as the central station for the Western Pacific VLBI network. The antenna is equipped with low noise receivers cooled with gas-helium refrigerators and has a band range from 1.5 GHz to 43 GHz. The surface accuracy is 0.17 mm (rms) at 45 degree elevation. The pointing accuracy of 0.002 degree (rms) enables the antenna to perform well on the millimeter wavelengths. Details of the 34 m antenna were described by Takaba et al. (1990)[1]. Although the original antenna had 300 MHz and 600 MHz feeds at the prime focus, we removed them in 1993 because it was very difficult to use these bands due to the effect of the strong interference signals. In addition we wanted to maximize the antenna's short wavelength efficiency.

Radio astronomy is one of the newest fields in astronomy and celestial radio waves from our galaxy were first detected in 1932. In recent years, the technology to construct large antennas and the

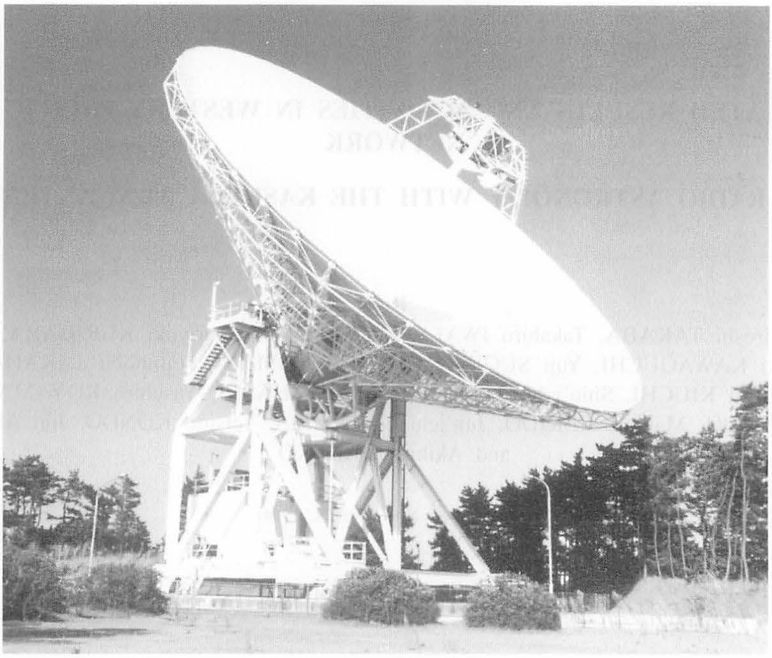

Fig. 1 CRL's 34 m antenna at Kashima Space Research Center

devices necessary to make low noise receivers has been developed, and our ability to detect very faint celestial signals has increased dramatically. Many new phenomena have been discovered and the study of the universe has been improved by the use of radio astronomy. Also, many new sources have been found, such as quasars which are very compact and emit very strong signals, pulsar which emit very accurate pulse-like signals, and other sources which have very strong maser lines. Besides their importance for radio astronomy, these objects are also very important because they are related to the measurement of time and space. This paper also introduces some of the applications of radio astronomy for antenna measurements, time keeping, and for solar-earth science.

2. Maser Observations

The first maser phenomena was found in 1966 and it was the astronomical maser observed in the dense gas around the regions where massive stars are formed. This discovery led to the study of artificial maser and laser physics. Details of astronomical masers were reviewed by Elitzur (1992)[2].

More than 100 interstellar molecules and ions have been discovered so far and of those about 10 molecules have maser transitions. Observations of such the interstellar molecular lines in the radio range provides us with data concerning the invisible dense gas in dark clouds, the mass losing red giants, the very young stars, and the centers of the galaxies.

The CRL 34 m antenna is capable of observing OH masers at 1.6 GHz, H_2O masers at 22 GHz, and SiO masers at 43 GHz bands. Maser comes from very small regions that are only measured by VLBI observations and they are considered to be point sources. Also, some maser sources are detected more than 100 K antenna temperatures by the large antennas. These maser sources can be

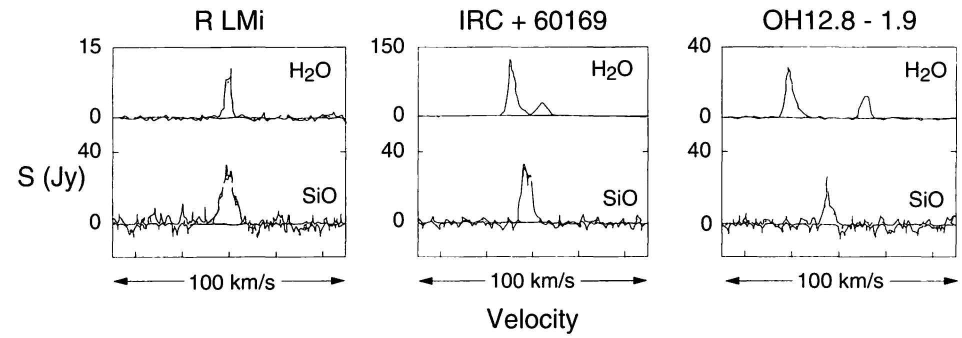

Fig. 2 (a) H_2O (upper) and SiO (lower) maser spectra in a Mira Variable, (b) an IRC/AFGL object, and (c) an OH/IR star. The data was obtained after 10 minutes integration by the 34 m antenna at Kashima using AOS.

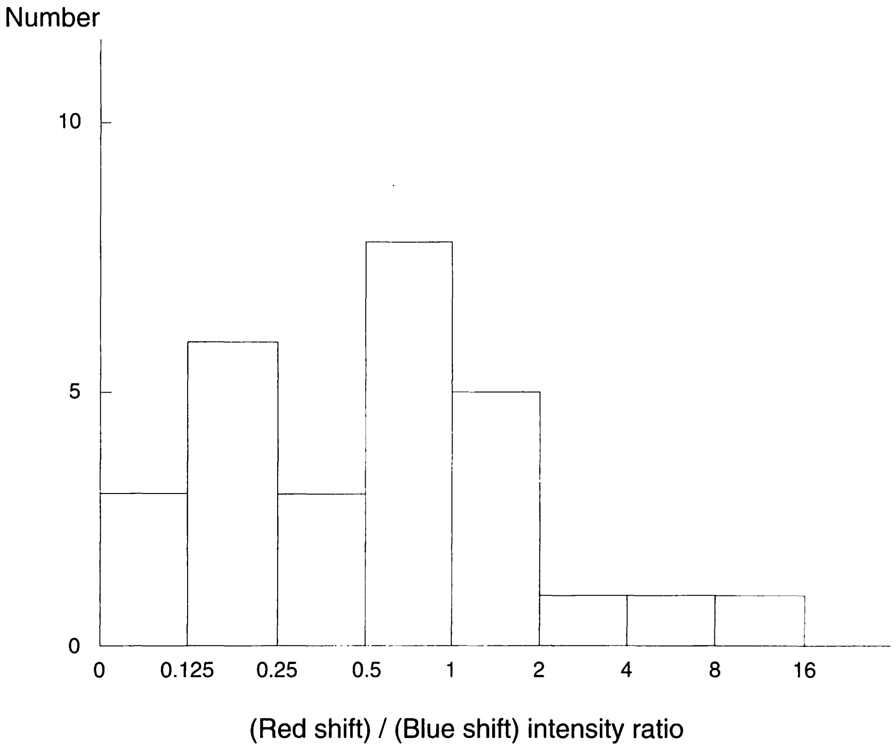

Fig. 3 Number distribution of the (Red-shifted)/(Blue-shifted) integrated intensity ratio for H_2O maser sources with separated peaks.

used to calibrate the pointing of the large antennas. By observing H_2O maser sources on the 22 GHz bands, Takaba (1991)[3] obtained the pointing parameters of the 34 m antenna within an accuracy of 0.002 degree (rms).

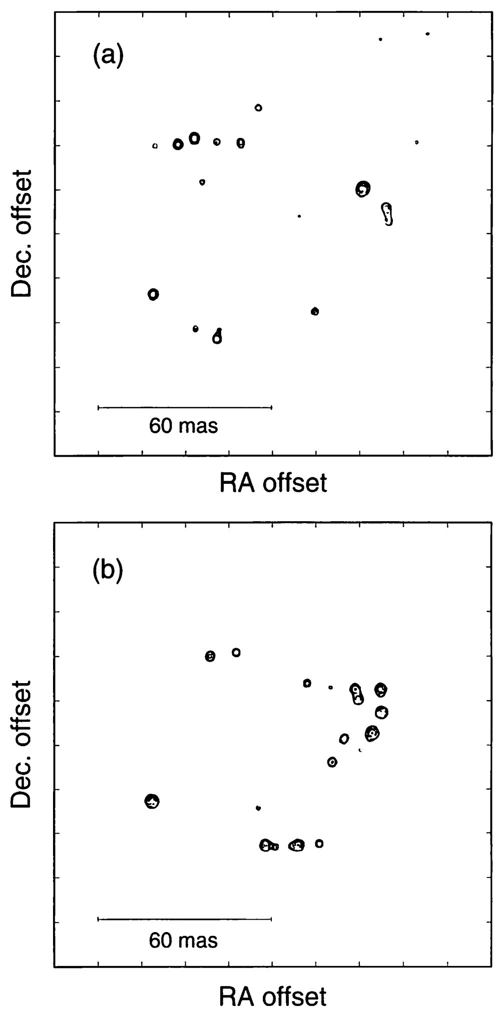

Fig. 4 Spatial distribution of SiO maser emission for W Hya for (a) the J = 1 – 0, v = 1 and (b) the J = 1 – 0, v = 2 transitions.

Single dish maser observations are done using an acousto-optical spectrometer (AOS) developed in Nobeyama and the 34 m antenna at Kashima. The H_2O maser survey at 22 GHz was started in 1991, and of the almost 900 infrared sources observed, 200 sources had H_2O maser emission, and about 50 sources were new detections[(4)]. By comparing the 22 GHz H_2O maser and 43 GHz SiO maser emissions of almost 300 known late type stars, Takaba et al. (1994)[(5)] found a systematic change in the H_2O maser spectra which can be used to trace the evolution of the late type stars (Fig. 2). These spectral changes can be explained by the collisional excitation of the H_2O molecules and the beaming effect taking into consideration the velocity fields of the gas surrounding the late type stars. The authors also found that the blue shifted emission was stronger than the red shifted emission in most sources which exhibited double peaked H_2O maser emissions (Fig. 3), and proposed the blocking effect with their beaming model. VLBI observations between the Kashima 34 m and the

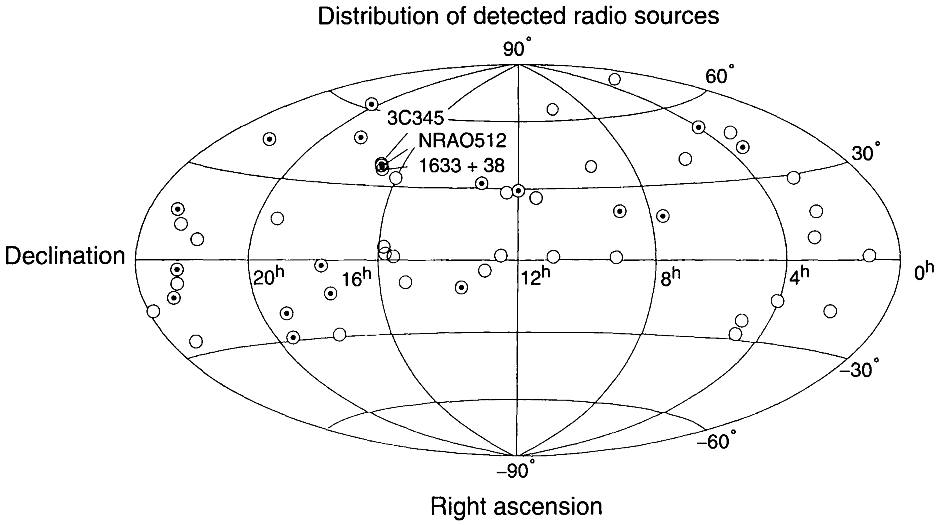

Fig. 5 Sky distribution of strong radio sources detected with KNIFE. Open circles represent the sources detected at 22 GHz, and dotted circles represent those detected at 43 GHz.

Nobeyama 45 m antennas are called KNIFE. Observations of H_2O maser in late type stars using KNIFE[6] show that the red shifted emission is highly resolved compared to the blue shifted emission. This result supports the idea of the blocking model.

Miyoshi et al. (1993[7], 1994[8]) observed SiO maser in late type stars using KNIFE. Two different transitions SiO(J = 1 − 0, v = 1) and SiO(J = 1 − 0, v = 2) were observed simultaneously and the results show that the two maser lines come from almost the same region (Fig. 4) which suggest the collisional excitation model. Since the two lines are about 300 MHz apart, we may use the band synthesis method by observing the two lines simultaneously. Then we may be able to obtain the absolute position in milli-arcsecond resolution. If this is true, we should be able to trace the galactic rotation by observing late type stars in our galaxy.

Strong H_2O masers are also found in star forming regions. Iwata et al. (1993)[9] reported the results of VLBI experiments using KNIFE. The maser emitting regions are found to be very close to the infrared source in dense molecular clouds.

3. Radio Continuum Observations

Quasars are very compact strong radio sources which are far from our galaxy. Recent studies indicate that quasars are the proto-galaxies which was created at the first stage of the universe and that they have massive black holes at their centers. There is considered to be a dense gas disk surrounding the black hole and some infall gas accelerating outwards, while its large gravitational energy is released. The mechanism is still unclear and the study of quasars is considered to be of major importance in order to investigate the evolution of the universe. Some quasars eject jet-like components from their cores and superluminal motions were detected in several sources. Strong quasars tend to have large time variation and it is thought that in such quasars the disk is face on to us and that the coming jets have strong radio intensities which peak at the millimeter wavelengths.

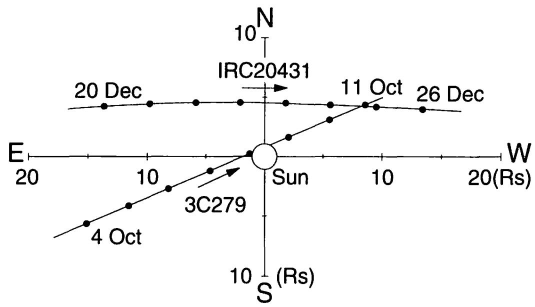

Fig. 6 The position of the radio sources, 3C279 and IRC 20431 relative to the sun as seen from the earth. 3C279 was observed at 2/8 GHz. IRC 20431 is an H_2O maser source and was observed at 22 GHz.

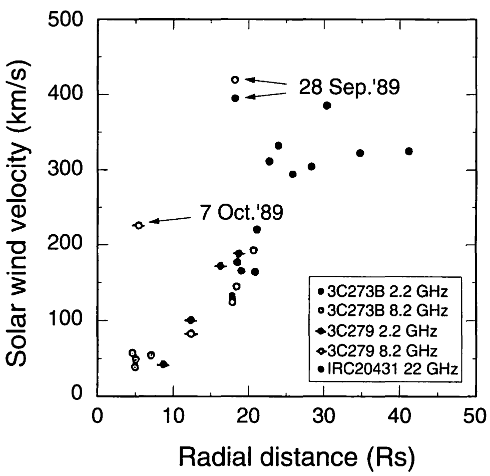

Fig. 7 The estimated solar wind velocity from the scintillation observations versus the radial distance from the sun.

Compact steep spectrum (CSS) objects are quasars with radio quiet spectrum[10]. Kameno et al. (1993)[11] and (1994)[12] observed CSS objects by KNIFE and reported the existence of the flat spectrum component at the central core of the sources. These results indicate that active cores also exist at the center of the CSS objects.

VLBI experiments for geodesy need wide bandwidths to obtain more accurate time delays. The ordinary geodesy VLBI experiments are carried out on the 2 and 8 GHz bands because those two bands are installed in most of the large antennas which use satellite communications. To obtain a wider bandwidth, higher frequency VLBI is required. The 22 GHz band should be the candidate frequency for wide bandwidth VLBI observation. Matsumoto et al., (1994)[13] surveyed strong radio continuum sources on the 22 GHz and 43 GHz bands using KNIFE and selected candidates for the geodetic VLBI on the 22 GHz band. The sky distribution of the strong radio sources on the 22 GHz and 43 GHz bands is found to be almost uniform (Fig. 5).

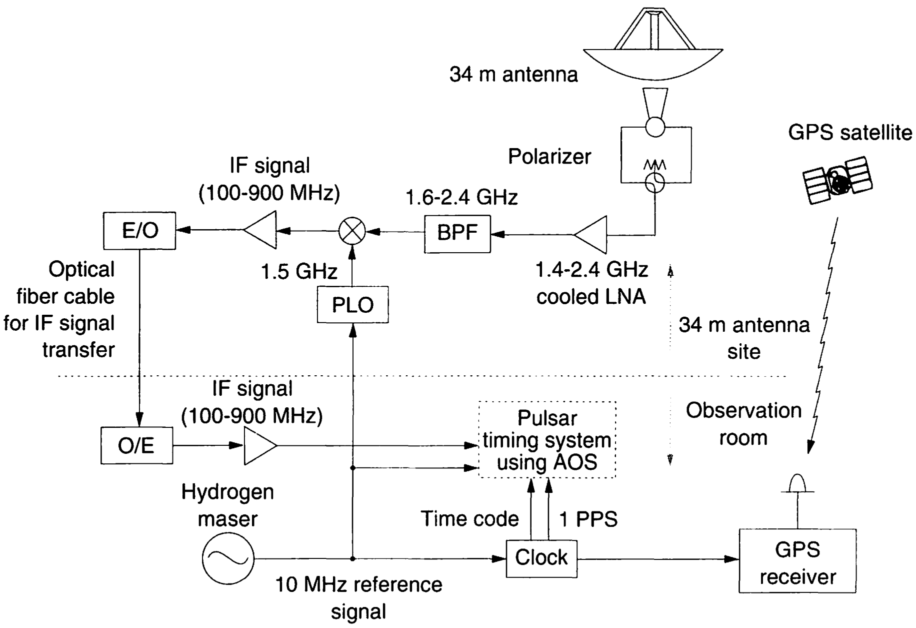

Fig. 8 New pulsar timing observation system developed by CRL. GPS receiving system and Hydrogen maser are used for precise time comparison.

4. Interplanetary Scintillation Observations

Quasars and maser sources are strong point sources in radio wavelengths and if we observe the intensity changes of the sources, we can determine the physical parameters of the interstellar medium. Interplanetary scintillation observations use sources which are distributed near the elliptic and observe the scintillation when the sun passes close to the sources.

By using the 34 m antenna, Tokumaru et al., (1991)[14] observed quasars on the 2 and 8 GHz bands, and H_2O maser sources at 22 GHz band (Fig. 6). The results show that there is a good correlation between the distance from the sun and the scintillation index. The derived solar wind velocity correlates well to the radial distance from the sun (Fig. 7). Also, some fluctuation in the acceleration near the sun is found. The observations are being continued for one solar activity cycle (11 years) and will produce new evidence that can be used to study the solar wind acceleration mechanism.

5. Pulsar Observations

Pulsars are rotating neutron stars and emit pulse-like signals. The newly discovered pulsars called millisecond pulsars have very stable pulse periods, in the order of milliseconds.

Most of the pulsars lose the rotation kinetic energy due to their interaction with the magnetic fields and the periods become longer. However, the millisecond pulsars are found to be the binary system and had been accelerated by obtaining the angular momentum from the companion star in the mass accretion process.

The millisecond pulsars are very old pulsars (they are thought to be more than 10 million years old) and the stellar systems are very stable, which results in very precise periods of rotation[15]. According to recent observations, the long-term stability of the millisecond pulsars is considered to be as stable as the atomic clocks on earth[16], and they may be even more stable than atomic clocks over longer time-scales (longer than 10 years). CRL has started pulsar timing observations in order to establish universal time keeping by using the millisecond pulsars[17].

The pulsar timing observation system developed at CRL is described by Hanado et al. (1994)[18]. This new system uses an acousto-optical spectrometer (AOS) to obtain a wide bandwidth (Fig. 8). Pulsars are also point sources, and they are good targets for VLBI observations. Hama et al., (1994)[19] reported the results of the pulsar VLBI observations between the Kashima 26 m and the Usuda 64 m antennas. The data obtained from pulsar VLBI observations will be useful for studying the physical characters of pulsars and also for radio astrometry because they are distributed throughout our galaxy.

6. Conclusion

Radio astronomical observations using the CRL's 34 m antenna are summarized. Maser observations, radio continuum observation, interplanetary scintillation observations, and pulsar observations are shown. These results show that in addition to the single dish observations, the contributions of the VLBI observations are very important for the study of radio astronomy and the application of radio astronomy for time and space measurements.

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V. CONCLUSION TOWARD THE KEY STONE PROJECT

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ABSTRACT

The main purpose of CRL's 5-year "Western Pacific Very Long Baseline Interferometer (VLBI) Network project" is to precisely measure the movement of the four tectonic plates under and around Japan: the North American Plate, the Pacific Plate, the Philippine Sea Plate, and the Eurasian Plate. This should help us learn how and why large earthquakes occur around the Japanese Islands, and our recent activities and achievements of the project are summarized in this special issue. The experience gained in this project provides the basis for a Tokyo Metropolitan Crustal Deformation Monitoring Program using space geodetic measurements and called "Keystone Project." This program will use both VLBI systems and Satellite Laser Ranging systems to monitor the three-dimensional displacement of four sites within the Metropolitan Tokyo region.

There are Japanese islands above the Pacific plate, the Eurasian plate, the Philippine Sea plate, and the North American plate. Because earthquakes occur very often in these islands, a VLBI network with a station on each plate should be constructed so that the relative motions of these plates can be monitored in order to obtain information that might be useful for the long-term prediction of earthquakes. We obtained a special fund from our government to construct such a network with a 30 m class antenna station at Kashima (supposedly on the North American plate) and two 10 m class antenna stations, one at Minamidaitojima (on the Philippine Sea plate) and one at Minamitorishima (on the Pacific plate).

In 1987, CRL purchased three antenna systems from USA: the 34 m antenna at the Kashima main station and 10 m and 11 m antennas for the remote islands. The 34 m antenna has a surface accuracy of 0.17 mm (rms), enabling it to be used at millimeter wavelengths. Ten low-noise radio-astronomy-frequency-band receivers (from 300 MHz to 43 GHz) are installed on the antenna, which replaced the 26 m antenna which had previously played the main role in CRL's international and domestic VLBI experiments. This 26 m antenna also has S/X band receivers and has been used for international VLBI experiments since 1984. Beside 34 m, 26 m antenna will play the important roles for international connection for our next new project. A 3 m antenna, the world smallest VLBI station, was also developed for mobile experiments. These antennas were completed in 1988, and have been the key stations for monitoring plate motion around Japan.

Our papers describe the performance of CRL's VLBI antennas and gives details of the new VLBI system including many new methods to calibrate for the accuracy of our results.

After the antenna system was checked in 1989, one antenna was transported to Minamitorishima (Marcus Reef), which is the only Japanese territory on the Pacific Plate, and the first VLBI experiment involving both Minamitorishima and Kashima was performed in July 1989. The following experiments using only the Japanese domestic VLBI network detected the clear movement of the Pacific Plate. For the Philippine Sea Plate, the 3 m antenna station was moved to and used for a

VLBI experiment with the Kashima 34 m antenna in 1990. In the same year, the 25 m antenna of the Shanghai Observatory joined in our Western Pacific VLBI Network as the reference station on the Eurasian Plate.

Space geodetic techniques such as VLBI, SLR, and the Global Positioning System (GPS) can monitor the global crustal motion or regional deformation with a precision better than a *few* centimeters. VLBI and GPS measure the baseline vectors, and VLBI is more suitable for longer baselines. SLR, however, measures the absolute geocentric position. VLBI and SLR play complementary roles to improve the three-dimensional precision of the global geodesy.

Based on both these progress of the space geodetic techniques and our experiences of The Western Pacific VLBI Network Project, we are now proceeding with the Tokyo Metropolitan Crustal Deformation Monitoring Program, called the "Keystone Project (KSP)," using space geodetic measurements. This project uses both VLBI and SLR to monitor the three-dimensional displacement of four sites around the Metropolitan Tokyo region. This region is on the edge of the North American Plate (or Okhotsk microplate) and also very near the boundaries of three other plates: Pacific Plate, Philippine Sea Plate, and Eurasian Plate. Thus, Tokyo region is situated above the very dangerous triple-layered structure of these three plates. It is now an urgent subject to monitor the preseismic signals of "the earthquake occurring directly under Metropolitan Area (EDUMA)."

VLBI and SLR are expected to make it possible to measure the horizontal relative displacements and the absolute vertical positions (with regard to the Earth's gravitational center) with a precision better than 1 cm, and this program will play a basic role for earthquake prediction in this area.

GPS geodetic networks now have been established mainly by Geographic Survey Institute (GSI) and the National Institute for Disaster Prevention and Earth Science (NIED). GSI and CRL have established the Metropolitan Diamond Cross (MDX) VLBI funded by the Science and Technology Agency of Japan, and two 3.5 m VLBI antennas have also been installed by GSI. These background also encouraged CRL to promote the new KSP to observe the crustal deformation around the Tokyo Metropolitan area. The Keystone Project is sensitive enough to measure both Type-1 (inner-plate earthquakes just beneath the surface) and Type-2 (occurring on the surface of Philippine Sea Plate) EDUMA in the southern Tokyo Metropolitan area and to measure Type-1 EDUMA in the northern Tokyo Metropolitan area.

Thus we will use and apply our global precise geodetic potential prepared by the Western Pacific VLBI Network to the urgent requirement for the earthquake prediction of our near-step Tokyo Metropolitan Area.