Vol. 48 No. 1 Journal of the Communications Research Laboratory March 2001
Printed in Tokyo, Japan pp. 3−11

2. VLBI Observation Results

2.1 International VLBI Experiments

By
Tetsuro KONDO and Taizoh YOSHINO

ABSTRACT

A 26-m antenna and 34-m antenna at the Kashima Space Research Center have played major roles in advancing both Japanese radio astronomy and worldwide geodetic VLBI. Achievements include the first successful VLBI measurement in history of Pacific-plate motion in 1985 and participation in an international experiment to make precise measurements of Earth rotation parameters in parallel. The Kashima Space Research Center has since participated in many international VLBI experiments and has contributed to the construction of a terrestrial reference frame (TRF) and celestial reference frame (CRF). Our activities at Kashima associated with international VLBI are reviewed.

Keywords: Kashima, Large antenna, VLBI, Radio astronomy, Geodesy

1. Introduction

The 26-m and 34-m parabolic antennas at the Kashima Space Research Center of the Communications Research Laboratory have played a major role in international geodetic VLBI in addition to making significant contributions to the advancement of radio astronomy in Japan. The history of large antennas at Kashima, however, goes back to the 1960's with the completion of a 30-m parabolic antenna in 1963 (Fig. 1). This antenna was originally developed to conduct satellite relay experiments during the 1964 Tokyo Olympics. At that time, however, there were no other antennas in Japan that could be used for radio astronomy observations. It was therefore decided that the 30-m antenna would also be used for this purpose in cooperation with the Tokyo Astronomical Observatory with the aim of developing radio astronomy in Japan. Then, in 1968, a 26-m parabolic antenna having good surface accuracy and high efficiency was constructed (Fig. 2). This antenna was also used actively for radio astronomy observations and contributed to the development of VLBI technology.

In 1974, the Radio Research Laboratories (present Communications Research Laboratory) began the development of a VLBI system (K-1) based on the Mark-II system developed in the United States. This system was used in Japan's first successful VLBI experiment in 1977 between the Kashima 26-m antenna and the 12.8-m antenna at the Yokosuka Electrical Communications Laboratories[1]. In 1979, a real-time VLBI system (K-2) using a microwave link between Kashima and Hiraiso was also completed, and in parallel with this development, a 5-year project got under way in the same year to develop a K-3 system that could be used for genuine geodetic VLBI observations. This K-3 system was designed to be compatible with the MARK-III system developed in the United States and to enable participation in the Crustal Dynamics Project (CDP)[2] led by the National Aeronautics and Space Administration (NASA) to measure plate motion. With this system, the first Japan-U.S. VLBI test observation was carried out in 1983 and participation in regular CDP experiments began in 1984[3]. The first successful measurement of Pacific-plate motion in history followed in 1985[4][5], and the K-3 system came to participate in international experiments to make precise measurements of earth rotation parameters in parallel. These observations helped to construct an international terrestrial reference frame (TRF) and celestial reference frame (CRF)[6]. The K-3 system has also participated in experiments associated with precise time syn-

Fig. 1 30-m parabolic antenna known for its contributions to Japanese radio astronomy (1963-1975)

Fig. 2 26-m parabolic antenna (1968-); contributed to first measurements in history of Pacific plate motion

chronization and radio astronomy observations.

Next, in fiscal year 1987, a supplementary budget was approved for the construction of a 34-m antenna (Fig. 3), and work began on the construction of a "Western Pacific VLBI Network" with the aim of measuring Pacific-plate motion near Japan[7]. Development of a compact and transportable VLBI system (K-4) was also undertaken in parallel with the construction of this network. The first successful test observations (Kashima-Tsukuba baseline) using the K-4 system were made in 1989. Following this, the K-4 system was used to make observations at Minamitorishima in the Western Pacific VLBI Network making a big contribution to measurements of Pacific-plate motion near Japan. Then, with the aim of applying results like these to precise crustal deformation observations in the Tokyo metropolitan area, the Key Stone Project (KSP) was launched in 1993[8][9][10]. In this project, a real-time VLBI system was developed with the aim of being the world's first continuously operating system of this kind[11]. This system contributed to a series of crustal-deformation detections that began with the Miyakejima eruption in June 2000[12].

As described above, the large antennas at Kashima have made great contributions not only to the advancement of Japanese radio astronomy but also to the fields of VLBI technology development and geodesy. For reference purposes, Table 1 lists those events in the history of the Kashima Space Research Center and Radio Astronomy Applications Section associated with large antennas and VLBI. In the following sections, we provide a review of international VLBI experiments at Kashima.

Fig. 3 34-m parabolic antenna (1988-); made great contributions to Japanese geodesy and radio astronomy

Table 1 History of large antennas at Kashima

August	1963	30-m parabolic antenna facilities completed
May	1964	Kashima office opened
February	1966	Radio astronomy observations initiated (in cooperation with Tokyo Astronomical Observatory)
October	1968	26-m parabolic antenna facilities completed
August	1970	Regular observations of quasars initiated (in cooperation with Tokyo Astronomical Observatory)
December	1973	Radio flare-up from X-ray star Cyg X-3 detected by 26-m antenna (first in world)
May	1975	30-m parabolic antenna dismantled
January	1977	First successful VLBI experiment performed in Japan (Kashima-Yokosuka)
October	1977	Present Radio Astronomy Applications Section established
April	1979	5-year project for VLBI Technology Development initiated (K-3 system development initiated)
December	1979	Operation of Kashima-Hiraiso real-time VLBI system (K-2) initiated (K-2 was Japan's first real-time VLBI system)
November	1982	Hardware compatibility test between K-3 and Mark-III VLBI systems successfully performed
November	1983	First successful Japan-U.S. VLBI preliminary experiment across the Pacific Ocean (Kashima-Mojave-Owens Valley) performed
January	1984	Japan-U.S. VLBI system-level experiment performed (January and February)
June	1984	Precise orbital determination for a Pacific geostationary satellite performed by the ΔVLBI method (Kashima-Goldstone-Canberra)
July	1984	International VLBI experiments initiated (participation in NASA's Crustal Dynamics Project) Distance between Japan and U.S. determined with an error of 2 cm
October	1984	Japan-U.S. time-synchronization experiments by VLBI initiated
November	1985	VLBI Earth-rotation (UT1) observations (GJRO) by a unique baseline performed
September	1985	Japan-China VLBI experiments initiated Distance between Kashima and Shanghai determined with ±3 cm
November	1985	Japan-U.S. VLBI experimental data analyzed and plate motion theory validated (Hawaii and Marshall Islands are approaching Japan at a rate of several cm a year)
July	1986	Participated in world's first space VLBI experiment using TDRSS
October	1986	Antenna-delay calibration experiment performed by zero-baseline VLBI (Kashima-Richmond) Japan's first VLBI-mobile-station (GSI Miyazaki) experiment performed; Japan's first data transfer and fringe check by telephone lines performed at the same time
Autumn	1987	Western Pacific VLBI Network project initiated
February	1988	Japan-Australia VLBI experiments initiated
March	1988	Western Pacific VLBI Network facilities (34-m antenna) completed
April	1988	"Radio Research Laboratory" name changed to "Communications Research Laboratory"
April	1988	VLBI observations in the Pacific-region Earth-rotation observation network (IRIS-P) initiated (in cooperation with National Astronomical Observatory)
July	1988	34-m antenna operation initiated
September	1988	Ultra-compact VLBI mobile experiment initiated (Koganei, Wakkanai, Okinawa)
May	1989	"Kashima Branch" name changed to "Kashima Space Research Center"
July	1989	First VLBI experiment between Minamitorishima and Kashima (Western Pacific VLBI Network) performed
September	1989	Interplanetary scintillation (IPS) observations using the 34-m antenna initiated
October	1989	Millimeter-wave (43 GHz) domestic (Kashima-Nobeyama) VLBI observations successfully performed

January	1990	History-first Antarctic VLBI (Kashima-Syowa) test observations successfully performed
March	1990	Japan-Canada (Kashima-Algonquin) VLBI experiment by the wavefront clock technique successfully performed
July	1990	Feasibility shown of ionosphere compensation for single frequency-band VLBI observations by total-electron-content measurements using GPS satellites
September	1990	Dual-band (S/X) simultaneous observations of IPS using the 34-m antenna and correlation analysis successfully performed
November	1990	Minamidaitojima VLBI experiment by an ultra-compact VLBI station (3-m antenna) successfully performed
January	1991	Millisecond pulsar successfully received by the 34-m antenna
February	1991	Japan-Italy 22-GHz geodetic VLBI experiment successfully performed
February	1991	ORTHO (Earth-rotation parameter-determination experiments using a group of north-south/east-west orthogonal base lines) performed (February and March)
June	1991	24-hour×1-week continuous VLBI experiment successfully performed (Minamitorishima)
November	1991	Maser radio source survey observations initiated
February	1992	Participated in gravity-wave detection experiment through Ulysses Doppler tracking observations
March	1992	Metropolitan VLBI (Kashima-Koganei-Tsukuba) observations successfully performed
October	1992	2.9-cm shortening of distance between Kashima and Shanghai over one year detected by VLBI
December	1992	Ownership of 26-m antenna transferred to Geographical Survey Institute of the Ministry of Construction
April	1993	Key Stone Project (to observe crustal deformation in the Tokyo metropolitan area) initiated
February	1994	First VLBI experiment with Urumqi station in China performed First fringe detection with Urumqi station performed
March	1994	11-m antennas for detecting crustal deformation in the Tokyo metropolitan area completed
July	1994	Radio astronomy observations in conjunction with collision of Shoemaker-Levy comet with Jupiter performed
August	1994	First VLBI observation of Key Stone Project performed
March	1995	Japan-Russia VLBI experiment performed
June	1995	Participated in gravity-wave detection experiment by Galileo-probe Doppler tracking observations
January	1996	Celestial body "Golevka" named after "Ka" in "Kashima" due to results of asteroid-radar international joint observations (performed in June 1995) using the 34-m radio telescope
April	1996	First fringe detection by ATM real-time VLBI performed
May	1996	Kashima Antlers mascot "Anton" drawn on Kashima's 34-m antenna
October	1996	Radar echo from asteroid 4197 successfully observed by the 34-m antenna
November	1996	Synchrotron radiation from Jupiter observations using the 34-m antenna initiated
December	1996	International workshop on space geodesy (TWAA96) held
May	1997	First fringe detection by space VLBI (VSOP) with the Kashima-HALCA baseline performed
June	1997	World's first 256-Mbps real-time VLBI regular observations initiated by the Key Stone Project
September	1997	VLBI observations by the Key Stone Project changed to bidaily 24-hour observations
July	1998	World's first VLBI experiment at a data recording speed exceeding 1 Gbps (4-times conventional speed) performed
December	1998	Real-time VLBI experiment with the ISAS Usuda 64-m antenna successfully performed
June	1999	Radar echo from Venus successfully observed by the 34-m antenna
October	1999	3-m antenna relocated to Gifu University

Autumn	1999	Real-time VLBI system based on Internet protocol (IP-VLBI) development started
December	1999	VLBI Symposium held at Kashima
January	2000	GIFT experiment (Kashima-Gifu) performed (geodetic experiment by a gigabit VLBI system)
July	2000	Crustal deformation detected at Tateyama station by KSP-VLBI observations in conjunction with Miyakejima eruption and earthquake activity in the Kozushima area; KSP operation changed to daily observations
August	2000	VLBI standard interface hardware specifications (VSI-H) established
November	2000	KSP-VLBI daily observations returned to normal operation (bidaily observations)

2. Participation in the Crustal Dynamics Project

The objective of the Crustal Dynamics Project (CDP) led by NASA was to perform high-precision measurements of plate motion and crustal deformation using space geodetic techniques like VLBI and satellite laser ranging (SLR) whose accuracy had improved remarkably in the 1980's[2]. At that time, VLBI was the superior technique for making high-precision measurements of intercontinental distances, achieving an accuracy of about 3 cm. It was therefore considered that measurements could be performed by VLBI observations over several years even for Pacific-plate motion predicted to be nearly 10 cm a year. Under these circumstances, the 26-m antenna at Kashima participated in regular CDP observations beginning in the summer of 1984. Figure 4 shows the station layout of the CDP experiment that Kashima participated in, and Fig. 5 shows the change in baseline length for Kashima-Hawaii and Kashima-Alaska as observed by a sequence of experiments. Here, the distance between the Kashima and Alaska stations is unchanged since they are both situated on the same plate (North American plate). (We note here that the northeastern section of Japan is considered by some to be on the Ohotsuku plate; relative motion between this plate and the North American plate, however, is very small.) The distance from Kashima to the Hawaii station (situated on the Pacific plate), however, shows an amount of change very close to the value predicted by the plate motion model of that time. By accumulating observation data, it has become possible to perform detailed comparisons between the plate motion model for average motion over several million years and plate motion over a short time scale of from several to ten years, and to see if they agree.

Figure 6 shows a vector display of horizontal movement per year of various stations with respect to the Eurasian plate. The broken line indicates predicted values. This figure is drawn by Mercator projection whose pole is taken to be the Euler pole (the pole of rotation used to describe plate motion). In the figure, Pacific plate motion is in the direction parallel to latitude, and it can be seen that the motion exhibited by the Vandenburg (California), Kauai (Hawaii), and Kwajalein (Marshall Islands) stations belonging the Pacific plate is nearly equal to that predicted by the plate motion model. The Kashima station, moreover, though belonging to the North American plate, is located near the boundary with

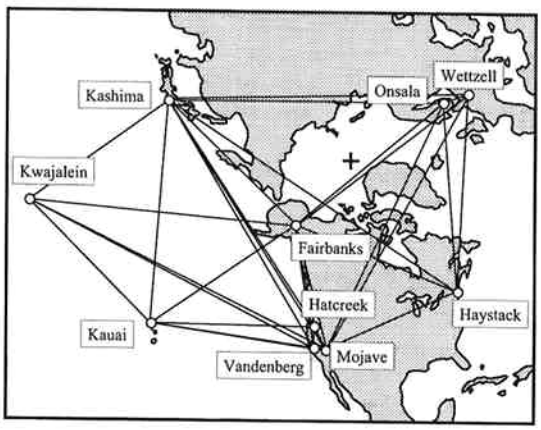

Fig. 4 Station layout of Crustal Dynamics Project (CDP) experiment that Kashima participated in

the Pacific plate, and change in its position has been observed in the same direction of motion as the Pacific plate. This is interpreted as change due to compression forces from that part of the Pacific plate that has subducted under Japan (Fig. 7)[13].

The CDP experiments also aimed to perform high-precision measurements of Earth rotation parameters (polar motion indicating the direction of the Earth's spin axis and UT1). The importance of adding Japan to these experiments that were initially performed between North America and Europe can be seen from the station layout in Fig. 1. Specifically, the addition of Kashima configures a set of baselines that encloses the North Pole making it possible to perform VLBI observations of polar motion with less bias. Taking advantage of this situation, intensive observations were carried out in 1985 between Kashima and the Wettzell station in Germany (GJRO) to look for short-term variations in UT1. These observations proved useful in clarifying systematic error in standard coordinates[14]. Other advanced experiments followed including Earth-rotation parameter-determination experiments in February 1991 using a group of north-south/east-west orthogonal base lines (ORTHO).

In addition, following the change in ownership of the 26-m antenna to the Geographical Survey Institute (GSI) in 1992, participation in regular international experiments took place in the form of GSI projects. In this way, Kashima continued to participate in CDP as well as the NASA lead Dynamics of the Solid Earth (DOSE) project, and participation has since expanded to the

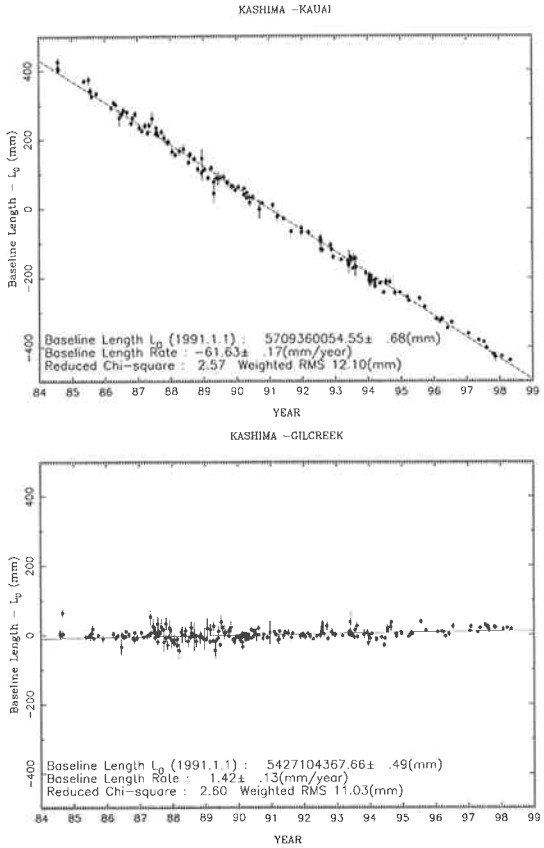

Fig. 5 Change in observed baseline length for Kashima-Kauai (Hawaii) and Kashima-Fairbanks (Alaska)

Continuous Observations of the Rotation of the Earth (CORE) project. With CORE, the objective is to make continuous measurements of Earth-rotation parameters and to eventually perform daily VLBI observations on a global scale.

3. Other International Experiments

While our participation in the NASA CDP experiment provided a great boost to the development of VLBI technology in Japan, we also participated in other VLBI experiments of various types and conducted international experiments that we ourselves planned. The section provides an outline of those experiments. Please see the references quoted for detailed information.

3.1 Time comparison experiment

One application of VLBI technology is to compare time between stations, and it enables clocks between continents to be compared with accuracy better than 1 nsec. This level of accuracy was confirmed in a VLBI experiment that took place between Kashima and Richmond in the United States (baseline length: 10280 km) in 1984. Compared to accuracy of about 10 nsec achieved in time comparisons by a portable clock and other conventional methods of that time, accuracy by VLBI technology was far better[15]. On the other hand, antenna and equipment offset are included in the time difference of clocks measured by VLBI, and these values must be removed to perform absolute time comparisons. To compensate for this

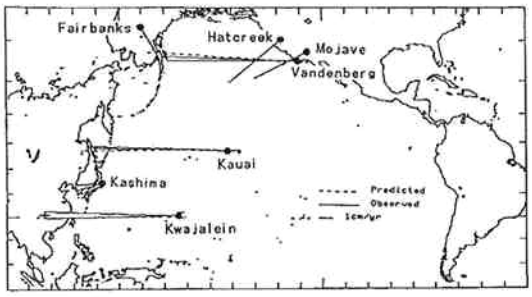

Fig. 6 Station movement relative to the Eurasia plate drawn by Mercator projection with pole taken to be the Euler pole (the pole of rotation used to describe plate motion)[13]

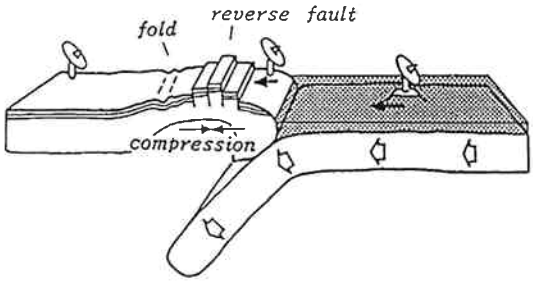

Fig. 7 Explanatory diagram of change in station position due to compression forces associated with Pacific-plate motion[13]

offset, we developed a portable reference receiver that could be mounted on a target antenna or installed nearby and developed observation technologies called zero-baseline-length VLBI (ZBI) and short-baseline-length VLBI (SBI). These technologies perform absolute time comparisons between stations by way of such reference receivers by making interferometric observations between such a receiver and a main antenna[16].

3.2 Space VLBI

In July 1986, the first space VLBI experiment in history was performed between a Jet Propulsion Laboratory (JPL) data relay satellite (TDRSS) and terrestrial antennas. In this experiment, Kashima's 26-m antenna played an important role as a complementary antenna to the Usuda 64-m antenna[17]. This experiment was followed by the VLBI Space Observatory Program (VSOP) promoted by the Institute of Space and Astronautical Science (ISAS), and as part of this project, the world's first space VLBI satellite called HALCA was launched in February 1997[18]. In this project, we cooperated with ISAS through the 34-m antenna participating in VLBI observations with HALCA and contributing to the first successful case of fringe detection in May 1997. Since then, we have also been contributing to achievements in radio astronomy.

3.3 Antarctic experiments

The first Japan-Australia VLBI experiment was conducted in 1988, and as we moved forward on Antarctic VLBI experimental projects, the Australian VLBI station came to play an important supporting role considering

the mutually poor visibility between the Kashima and Syowa stations. In 1990, with the cooperation of the Australian VLBI station, the first Antarctic VLBI experiments in history (between the Kashima 26-m antenna and Syowa 11-m antenna) were performed as a joint project with the National Institute of Polar Research (NIPR). At the Syowa station, a multipurpose antenna for satellite communications was constructed in 1989, but to enable VLBI experiments to be performed, a K-4 system was transported to the station. Also, because of the difficulty of shipping a hydrogen-maser frequency standard at the time, a system developed by CRL called a "cesium-X'tal clock" was used in the experiments as a frequency standard[19]. All in all, two 24-hour experiments were performed among three stations including Australia's Tidbinbilla station, and the position of the Syowa-station antenna was determined with an error of 20 cm, as shown in Fig. 8[20]. The success of these experiments led to the launching of geodetic VLBI projects at the NIPR and the introduction of a VLBI system with a hydrogen-maser at the Syowa station. At present, the NIPR and the Geographical Survey Institute are moving forward with full-scale Antarctic VLBI experiments.

3.4 Japan-China experiments

In 1983, at the 2nd Japan-China Science and Technology Cooperation Conference held in Tokyo, an agreement was reached between the Shanghai Astronomical Observatory and Communications Research Laboratory to conduct joint VLBI experiments. The first VLBI experiment based on this agreement took place in 1985 on the Kashima-Shanghai baseline. For these observations, a K-3 system and a recently developed recorder featuring a helical-scanning VTR (which would lead to the development of the K-4 recorder) were carried to Shanghai. The end result was a successful VLBI experiment between the 26-m antenna in Kashima and the 6-m antenna in Shanghai indicating that the length of this baseline was contracting at a rate of about 3 cm a year (Fig. 9). This value, however, turned out to be much larger than the value expected from the relative plate motion model between the Eurasian plate that Shanghai is on and the North American plate that Kashima is on. It was a large value even when considering the Kashima motion caused by Pacific-plate motion. An analysis was therefore performed on movement in Shanghai's position on a horizontal plane, and it was found that a displacement in the Eurasian plate occurs in the east-southeast direction. This is attributed to the influence of the northward moving India plate as this plate collides with the Eurasian plate and creates the Himalayan mountain range, the eastern section of the Eurasian continent moves east as the Amur plate independently of the stable section of the Eurasian plate[21][22].

The second Chinese VLBI station was constructed in Urumqi in 1992, and at the request of the Urumqi Observatory director, the Communications Research Laboratory cooperated extensively in the startup of the Urumqi station. In February 1994, a K-4 system was brought into the Urumqi station, and the first VLBI experiment on the Kashima-Urumqi baseline was performed resulting in successful fringe detection and baseline-length determination within ± 3 cm[23].

3.5 Japan-Canada wavefront clock experiment

An experiment to evaluate the feasibility of the wavefront clock (WFC)[24] technique in VLBI experiments on intercontinental baselines was performed in March 1990 between the 34-m antenna at Kashima and the 45-m antenna at Algonquin in Canada. The WFC technique as applied to VLBI compensates for the Doppler shift (fringe phase rotation) caused by the Earth's rotation by artificially controlling the clock rate in the frequency standard at the time of observation. This technique negates the need for fringe-stopping operations during correlation processing, and can also minimize coherence loss in the case of large Doppler shift such as in space VLBI. There was therefore a need to validate the effectiveness of this technique for a long east-west baseline in which a large Doppler shift occurs. In this regard, the Kashima-Algonquin baseline (baseline length of about 9100 km) was considered ideal. At that time, however, there was no VLBI terminal at the Algonquin station, and data was consequently input to a computer hard disk and correlation processing was performed by a computer, an advanced approach for that time. As a result, good fringe

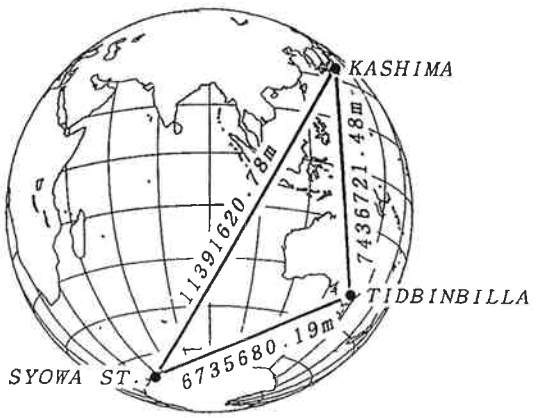

Fig. 8 Layout of stations participating in Antarctic VLBI experiment

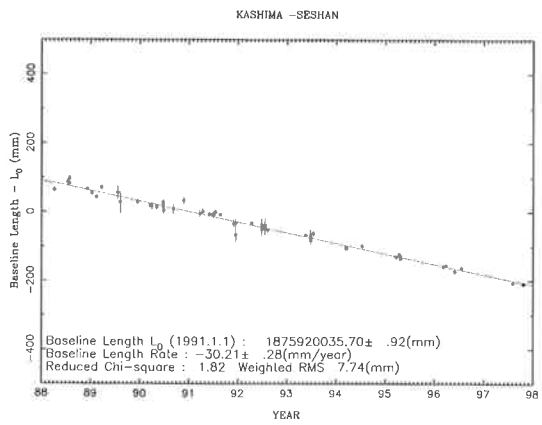

Fig. 9 Change in Kashima-Shanghai baseline

detection was achieved and the usefulness of the WFC technique was validated[25].

3.6 Other experiments

Reception in geodetic VLBI experiments has been traditionally performed in the 2-GHz and 8-GHz bands. To explore the possibility of geodetic VLBI experiments at higher frequencies, a geodetic VLBI experiment at 22 GHz was performed in 1991 between Kashima and Medicina in Italy. Although there was a need to generate a phase-calibration (PCAL) signal by some means in the 22-GHz band, the experiment was successful in obtaining a level of precision equivalent to that of geodetic VLBI in the 2/8-GHz bands by adopting a frequency-conversion method to generate PCAL signals[26].

In addition, for several years starting in 1988, experiments associated with International Radio Interferometric Surveying in the Pacific region (IRIS-P) were performed once a month in cooperation with the National Astronomical Observatory at Mizusawa. In these experiments, the National Astronomical Observatory at Mizusawa, the analysis center for the International Earth Rotation Service (IERS), created observation schedules and organized the participating stations[27]. As a result of these experiments, considerable progress was made in understanding systematic error in standard coordinates compared with other international experiments[28].

4. Summary

In this article, we have surveyed the role played by large antennas at Kashima in international VLBI experiments especially in relation to geodesy. Perhaps the most noteworthy achievement in geodetic VLBI that a Kashima antenna has been connected with is the first measurement of Pacific-plate motion. In addition, there are many other "first time in history" experiments that these large antennas have participated in, and the important role played by Kashima in advancing both Japanese and world VLBI technology and contributing to scientific achievements has again been recognized. We note here that space geodetic technology has made remarkable progress in recent years, and that the Global Positioning System (GPS) can now make geodetic measurements at the same level of accuracy as that of VLBI. At present, the Geographical Survey Institute is performing crustal deformation observations through a GPS observation network consisting of more than 1000 points in Japan. Performing observations with such a high spatial density, though, is difficult for VLBI in terms of cost, but on the other hand, we expect VLBI observations to be used to check the accuracy of GPS observations and to provide calibration points. Furthermore, the comparison of measurement results by different space geodetic technologies like VLBI, GPS, and SLR is now a "hot" research field, and data obtained by the CRL Key Stone Project is also being used for this purpose.

At the same time, geodetic VLBI is indispensable to coupling the terrestrial reference frame and celestial reference frame and measuring Earth rotation parameters (direction of the Earth's spin axis and UT1) with no bias. Moreover, it is expected to play an important role in measuring the position of future space probes from the Earth. Currently, with the aim of making real-time VLBI technology as applied in KSP more practical, we are working on the development of Internet-based real-time VLBI technology (IP-VLBI). The establishment of IP-VLBI should facilitate real-time VLBI observations by international baselines and enable Earth rotation parameters to be determined in a quasi-real-time manner that should contribute to improving GPS accuracy.

References

(1) Very Long Baseline Interferometry (VLBI) Experiments, Special Issue, Review of the Radio Research Laboratory, Vol.24, No.130, 1978. (In Japanese)

(2) J.C. Robert, H. Frey, G.D. Mead, and J.M. Bosworth, "Space-age geodesy: The NASA Crustal Dynamics Project", IEEE Trans. Geosci. Remote Sensing, Vol.GE23, No.4, pp.360-368, 1985.

(3) K-3 Very Long Baseline Interferometry (VLBI) System Development, Special Issue, Review of the Radio Research Laboratory, Vol.30, No.1, 1984. (In Japanese)

(4) T. Kondo, K. Heki and Y. Takahashi, "Pacific plate motion detected by the VLBI experiments conducted in 1984-1985", J. Radio Res. Lab., 34, 1-14, 1987.

(5) K. Heki, Y. Takahashi, T. Kondo, N. Kawaguchi, F. Takahashi, and N. Kawano, "The relative movement of the North American and Pacific plates in 1984-1985, detected by the Pacific VLBI network", Tectonophysics, 144, 151-158, 1987.

(6) C. Ma, J.W. Ryan, D. Gordon, D.S. Caprette, and W.E. Himwich, "Reference frames from CDP VLBI data", Contributions of Space Geodesy to Geodynamics: Earth Dynamics Geodynamics 24, pp.121-145, 1993.

(7) Special Issue of the CRL Journal on "Western Pacific VLBI Network", J. Commun. Res. Lab., Vol.42, No.1, pp.3-110, 1995.

(8) Crustal Deformation Observation System in the Tokyo Metropolitan Area, Special Issue, Review of the Communications Research Laboratory, Vol.42, No.1, 1996. (In Japanese)

(9) Key Stone Project —Crustal deformation monitoring system around the Tokyo Metropolitan area—, J. Commun. Res. Lab., Vol.46, Special Issue No.1, 1999.

(10) Y. Koyama, N. Kurihara, T. Kondo, M. Sekido, Y. Takahashi, H. Kiuchi, and K. Heki, "Automated geodetic Very Long Baseline Interferometry observation and data analysis system", Earth, Planets and Space, 50, 709-722, 1998.

(11) H. Kiuchi, M. Imae, T. Kondo, M. Sekido, S. Hama, T. Hoshino, H. Uose, and T. Yamamoto, "Real-time VLBI system using ATM network", IEEE Trans. Geosci. Remote Sensing, Vol.38, pp.1290-1297, 2000.

(12) F. Kimata and T. Tabei, "Crustal Deformation and Tectonics in Kozu/Niijima Area based on GPS Observations", The Earth Monthly, Vol.22, No.12, pp.837-846, 2000. (In Japanese)

(13) K. Heki, "Direct measurement of plate motion", J. Commun. Res. Lab., Vol.38, No.3, pp.521-531, 1991.

(14) T. Yoshino, S. Hama, T. Shiomi, J. Campbell, H. Cloppenburg, H. Schuh, and R. Kilger, "First VLBI experiments between Kashima and Wettzell for monitoring UT1", Adv. Space Res. Vol.6, No.9, pp.13-16, 1986.

(15) T. Yoshino, "International VLBI experiments between 1984 and 1990", J. Commun. Res. Lab., Vol.38, No.3, pp.513-520, 1991.

(16) S. Hama, H. Kiuchi, Y. Takahashi, J. Amagai, and T. Yoshino, "Japan-U.S. time comparison experiment for realizing better then 1-ns accuracy by using a radio interferometric technique", IEEE Trans. Instrumentation and Measurement, Vol.38, pp.640-643, 1989.

(17) G.S. Levy, R.P. Linfield, C.D. Edwards, J.S. Ulvestad, J.F. Jordan, Jr., S.J. DiNardo, C.S. Christensen, R.A. Preston, L.J. Skjerve, L.R. Stavert, B.F. Burke, A.R. Whitney, R.J. Cappallo, A.E.E. Rogers, K.B. Blaney, M.J. Maher, C.H. Ottenhoff, D.L. Jauncey, W.L. Peters, J. Reynolds, T. Nishimura, T. Hayashi, T. Takano, T. Yamada, H. Hirabayashi, M. Morimoto, M. Inoue, T. Shiomi, N. Kawaguchi, H. Kunimori, M. Tokumaru, and F. Takahashi, "VLBI using a telescope in earth orbit. I. The observations", Astrophys. J., 336, 1098-1104, 1989.

(18) H. Hirabayashi, "The VSOP mission —A new era for VLBI, Radio Emission from Galactic and Extragalactic Compact Sources", ASP Conference Series, Volume 144, IAU Colloquium 164, eds. J.A. Zensus, G.B. Taylor, and J.M. Wrobel, p.11, 1998.

(19) H. Kiuchi, S. Hama, J. Amagai, T. Yoshino, and M. Imae, "A highly stable crystal oscillator applied to the VLBI reference clock", IEEE-IM, Vol.45, No.1, Feb. 1996.

(20) N. Kurihara, T. Kondo, Y. Takahashi, and M. Ejiri, "The results of test VLBI experiments with the Syowa station in Antarctica", J. Commun. Res. Lab., Vol.38, No.3, pp.605-611, 1991.

(21) K. Heki, Y. Koyama, N. Kawaguchi, J. Amagai, H. Kuroiwa, S. Hama, Z.H. Qian, S.H. Ye, L.D. Wu, D.M. Hua, S.D. Xu, M. Imae, N. Kurihara, Y. Sugimoto, T. Yoshino, F. Takahashi, H. Kiuchi, Y. Takahashi, H. Takaba, T. Iwata, Y. Hanado, M. Sekido, T. Kondo, and A. Kaneko, "Movement of the Shanghai station: Implication for the tectonics of eastern Asia", J. Commun. Res. Lab., Vol.42, No.1, pp.65-72, 1995.

(22) K. Heki, "Horizontal and vertical crustal movements from three-dimensional very long baseline interferometry kinematic reference frame: Implication for the reversal timescale revision", J. Geophys. Res., Vol.101, B2, pp.3187-3198, 1996.

(23) T. Iwata, J. Nakajima, M. Sekido, Y. Takahashi, K. Heki, M. Imae, Y.S. Dong, B. Deng, Z.H. Qian, and R.X. Zhou, "Short report of the experiments with the Urumqi VLBI station, western China", J. Commun. Res. Lab., Vol.42, No.1, pp.81-84, 1995.

(24) H. Kiuchi and T. Kondo, "The Wavefront Clock Technique Applied to Current VLBI Systems", Publ. of the Astronomical Society of Japan, Vol.48, pp.137-146, 1996.

(25) H. Kiuchi, T. Kondo, and J. Popelar, "International VLBI experiment using the wave-front clock techniq ue", J. Commun. Res. Lab., Vol.38, No.3, pp.577-604, 1991.

(26) Y. Takahashi, H. Kiuchi, N. Kurihara, G. Grueff, and R. Ambrosini, "The first geodetic VLBI experiment at 22 GHz between Japan and Italy", Astronomy and Astrophysics, Vol.282, pp.341-348, 1994.

(27) K. Yokoyama, S. Manabe, T. Hara, T. Yoshino, and Y. Takahashi, "The earth rotation parameters determined with the new IRIS-P VLBI network", Vistas in Astronomy, Vol.31, pp.657-662, 1988.

(28) T. Yoshino, Y. Takahashi, N. Kawaguchi, K. Heki, K. Koyama, and S. Manabe, "Intercomparison of the Earth rotation parameters determined by two different independent VLBI networks", Astron. Astrophys., Vol.224, pp.316-320, 1989.