Application of Space Techniques to Geodesy and Geodynamics in Japan

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VLBI, SLR, and GPS have been introduced and used to study geodesy and geodynamics in Japan as well as elsewhere in the world. The present article briefly overviews Japanese recent activities concerning the applications of these techniques. VLBI and SLR have been used mainly in international experiments such as the Monitor Earth Rotation and Intercompare Techniques (MERIT) campaign and the Crustal Dynamics Project (CDP). These projects have succeeded in determining the relative plate motions around the Japanese Islands. GPS, on the other hand, has been used mostly to monitor local crustal deformations for earthquake prediction research. The combination of these techniques may lead us to a unified view of crustal deformation and the dynamics of the upper mantle.

1. Introduction

Precise positions of observers on the earth and orbiting objects in space are the most fundamental information for geodesy and geophysics. Centimeter accuracies in estimating both absolute positions and baseline vectors with a global consistency have been achieved by space techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and the Global Positioning System (GPS).

Results from VLBI and SLR first opened a new era in various fields of geosciences. Progress in Earth rotation studies (e.g., Tapley *et al.*, 1985; Campbell *et al.*, 1987) and determining a terrestrial reference frame (e.g., Boucher *et al.*, 1993) in geodesy and detection of plate motion (e.g., Christodoulidis *et al.*, 1985; Herring *et al.*, 1986; Heki *et al.*, 1987) in geodynamics are the most eminent examples.

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VLBI and SLR have been developed since the late 1960s. In the latter half of the 1970s, these techniques became accurate enough to detect plate motions and small variations of earth orientation parameters. Since contemporary plate motions were found for the first time to be consistent with geological evidence by VLBI and SLR, space techniques became the most reliable and useful geodetic tools used by geoscientists.

GPS has been developed since the early 1970s and its interferometric use became available in the early 1980s. Then, the technique has been improved rapidly in about 10 years, and the accuracy in estimating baselines or Earth rotation parameters has become comparable to other space techniques (e.g., Herring *et al.*, 1991; Lindqwister *et al.*, 1992; Lichten *et al.*, 1992).

In the present article, we briefly overview Japanese activities related to these space techniques and introduce recent results. We also discuss problems in these techniques and future possibilities. Especially emphasized is the importance of the close tie of coordinates obtained independently by these various techniques.

2. Very Long Baseline Interferometry

2.1 Summary of geodetic VLBI activities in Japan

Three organizations are conducting most of the geodetic VLBI experiments in Japan. They are the Communications Research Laboratory (CRL, formerly Radio Research Laboratories; RRL) of the Ministry of Posts and Telecommunications, the Geographical Survey Institute (GSI) of the Ministry of Construction, and the National Astronomical Observatory (NAO) of the Ministry of Education, Science and Culture.

CRL has developed VLBI systems successively as K-1, K-2, K-3 (Kawaguchi *et al.*, 1982) and K-4 (Kiuchi *et al.*, 1991; Hama and Kiuchi, 1991) types. These systems have been used at the Kashima VLBI station to conduct domestic and international joint experiments with other institutions, for the past 15 years. The major activity for measuring plate motions began in 1980 when NASA and RRL agreed to start joint VLBI experiments. Shortly later, RRL succeeded in developing the K-3 type VLBI system which is compatible with the Mark-III system of the USA. Since the start of joint experiments in 1984, RRL (now CRL) has carried out many joint experiments with other countries such as the USA, China, Germany, Australia, Canada, Sweden, Italy, etc. (Takahashi, 1991), as well as domestic experiments (Imae, 1991). These experiments are not only for plate motion measurements but also for geodetic controls, international time comparisons and earth rotation observations. Since the Kashima station is located near a convergent plate boundary where crustal activity is high (Fig. 1), VLBI data including Kashima have yielded interesting results for tectonic studies as will be described in the following section.

GSI has constructed a mobile 5m VLBI antenna and introduced the K-3 type VLBI system for domestic VLBI experiments in 1984 with technical support by CRL. After its completion, GSI and CRL started cooperative domestic experiments between Kashima station and GSI's mobile station in 1986. By 1992, several mobile sites have been occupied by GSI to control geodetic networks in Japan with unprecedented high accuracies (Tobita *et al.*, 1993); these studies have detected plate motions (Matsuzaka *et al.*, 1991).

Fig. 1. Tectonic environments around Japanese islands and VLBI (●) and SLR (■) sites in Japan. PCFC, Pacific plate; PHIL, Philippine Sea plate; EURA, Eurasian plate; NOAM, North American plate. The plate boundary between NOAM and EURA (hatched lines) is controversial (DeMets, 1992).

NAO also has introduced VLBI system. They intend to apply VLBI technique for various studies such as Earth rotation studies, astronomy and planetary sciences (e.g., Kawano *et al.*, 1992). NAO first installed a 6 m antenna at the Nobeyama Radio Observatory of NAO and recently constructed a 10 m antenna at Mizusawa. Using the latter antenna, they first determined the site coordinate of Mizusawa and began to participate in the International Radio Interferometric Surveying-Pacific (IRIS-P) VLBI campaign in 1993 (Kameya *et al.*, 1994).

2.2 Results of the international geodetic VLBI experiments

The results of the VLBI experiments that CRL has participated in are summarised by Yoshino (1991), Heki (1991), and Kondo *et al.* (1992). Readers are asked to refer to these papers for detailed documentation. The following is a summary of these works.

After the completion of the K-3 VLBI system, CRL started to participate in NASA's Crustal Dynamics Project (CDP) under US-Japan cooperation agreements. It has been mainly participating in the Pacific and the Polar VLBI experiments of CDP. The Pacific network contains stations on the Pacific and the North American plates. The Polar network consists of stations on the North American and the Eurasian plates. The changing rates of the baseline length were obtained from the slopes of straight lines fitted to the baseline length data estimated from individual observing sessions (Heki *et al.*, 1990).

The question whether the northeastern Japan is located on the Eurasian plate (e.g.,

Chapman and Solomon, 1976) or on the North American plate (e.g., Nakamura, 1983; DeMets, 1992) is controversial. Seno (1985), on the other hand, proposed another possibility: that northeastern Japan is a micro-plate. It thus seems important to monitor the displacement of Kashima, because it is located in the northeastern Japan.

Significant contractions of the Kashima–Kauai and Kashima–Kwajalein baselines were first detected in 1985 and their rates showed good consistency with the RM2 plate motion model of Minster and Jordan (1978) (Heki *et al.*, 1987). This was one of the earliest detections of actual plate motion, along with the detection of Eurasian–North American relative plate motion (Herring *et al.*, 1986). Figure 2 shows the baseline length change in the Kashima–Kauai baseline for data obtained from 1984–1991 (Ryan *et al.*, 1993). The observed slope of the best-fit line is -4.51 ± 0.03 cm/year, which shows a good agreement with the NUVEL-1 plate motion model (DeMets *et al.*, 1990), assuming that Kashima is located on the North American plate.

Global plate motion models such as RM2 or NUVEL-1 were derived basically from geological data sets such as ocean magnetic anomalies, slip directions of interplate earthquakes and the strike of transform faults. VLBI results showed that plate motion is quite steady over the time scale from a few years to millions of years.

This success of space techniques made it possible to study plate motions in more detail. Further investigations of results suggest considerable difference or inconsistency of VLBI data with simple rigid plate motion models. Heki *et al.* (1990) suggested, for example, that, in the Pacific region, we cannot simply compare the observed and predicted changes because most of the stations are so close to plate boundaries that the displacement at such VLBI sites may be contaminated by local deformation. Among the circum-Pacific stations, Fairbanks station in central Alaska is the only station in a stable interior. The change in the Fairbanks–Kauai baseline length is predicted to be -5.0 cm/year by RM2. This is higher by 10% than that of NUVEL-1 (-4.5 cm/year). This is considered below in the discussion section.

2.3 Results by Japanese geodetic VLBI experiments

2.3.1 JEG and VEGA series VLBI experiments

CRL and GSI are performing two series of VLBI experiments as joint projects: one is led by CRL and named the Japanese Experiments for Geodesy (JEG), which

Fig. 2. Length changes for Kashima–Kauai VLBI baseline; data taken from the experiments for the period of 1984–1991 (Ryan *et al.*, 1993).

measures the baseline between Kashima and Tsukuba; the other is led by GSI and named VLBI Experiments for Geodetic Applications (VEGA) which measures baselines between various sites in Japan and Kashima.

The chief objectives of the JEG is (1) to establish a domestic standard VLBI baseline by repeated experiments on the Kashima-Tsukuba baseline of about 54 km, and (2) to check new facilities such as the K-4 type VLBI system developed by CRL. Ten 24 h VLBI experiments (Amagai, 1991) have been performed between Kashima and Tsukuba up to 1990. The baseline lengths obtained by JEG agree with an optical surface measurements to within 9 cm. Considering that the precision of the optical measurement is about 10 cm, on one hand, and that the repeatability of the baseline vector was better than 1 cm, on the other hand, the result may show that the Kashima-Tsukuba standard baseline has now been established.

For the VEGA series, GSI has been transporting its mobile VLBI antenna system once a year to different locations around Japan since 1986. VLBI experiments have been performed with Kashima VLBI station to establish a precise geodetic network in Japan. They have occupied so far Shintotsukawa in Hokkaiko, Mizusawa in Tohoku, Chichi-jima in the Bonin Islands, Sagara in Chubu district and Miyazaki in Kyushu (Fig. 1). GSI has reoccupied Chichi-jima and Miyazaki (Tobita *et al.*, 1993). In the two experiments occupying Chichi-jima island in 1987 and 1989, Matsuzaka *et al.* (1991) detected movement of the Philippine Sea plate for the first time (Fig. 3). Tobiba *et al.* (1993) analyzed these data except Sagara and obtained site coordinates in the IERS Terrestrial Reference Frame 1989 (ITRF89) for the epoch 1988.0.

2.3.2 Experiments by highly transportable VLBI station

In 1984, CRL started developing a highly transportable VLBI station with a 3-m antenna and completed it in 1987 (Amagai *et al.*, 1989). CRL also cooperated with GSI to construct a transportable system with a 2.4 m antenna (Takahashi *et al.*, 1992). This station is the world's most compact antenna system for VLBI experiments. This station also incorporates the K-4 VLBI system, developed by CRL, with a simple and easy-to-use frequency standard consisting of a Cesium clock and a high-stability crystal oscillator (Kiuchi *et al.*, 1989). In order to achieve measurement precision which matches ordinary VLBI experiments, a wide receiving bandwidth is used for this small antenna system.

Fig. 3. Displacement vectors at Chichi-jima VLBI site relative to Kashima. Solid arrow and oval show the VLBI results and its 2 sigma error ellipse, respectively. Broken arrows and oval are the predicted displacement and its 2 sigma, respectively (after Matsuzaka *et al.*, 1991)

From 1988 to 1989, a series of mobile VLBI experiments were performed at the following CRL stations; the headquarters in Koganei, Wakkanai radio observatory in Hokkaido, and Okinawa radio observatory. The aim of these experiments was to test the performance of this station and to establish reference points for determining the precise orbit of GPS satellites (Sugimoto *et al.*, 1989). The highly transportable VLBI station was also moved to Minami-daito island on the Philippine Sea plate as part of CRL's Western Pacific VLBI Network as described in the following section.

2.3.4 Western Pacific VLBI network

In 1987, CRL set up three antenna systems: a 34-m antenna at the Kashima main station and two 10-m class antennas on the remote islands, Minami-torishima and Minami-daito island (Takaba, 1991; Takaba *et al.*, 1991). The 34-m antenna replaced the 26-m antenna which had previously played the main role in CRL's VLBI experiments. The "Western Pacific VLBI Network project" was a 5 year VLBI project started by CRL. The major purpose of this project was precise measurements of movement of the four plates in and around Japan (Fig. 1).

In 1989, after a system check of the antenna system, one of the 10-m antenna was transported to Minami-torishima (Marcus Island) which is the only Japanese territory on the Pacific plate. VLBI experiments between Minami-torishima and Kashima were first performed in July 1989 and were continued annually until 1993 (Koyama, 1991; Kondo *et al.*, 1992; Koyama *et al.*, 1994).

Figure 4 shows the change of baseline length between Kashima and Minami-torishima detected by the 5 years of Western Pacific VLBI network observation. The baseline encompasses the plate boundary between the Eurasian and the Pacific plates and the resultant lateral displacement showed a good agreement with the NNR-NUVEL-1 plate motion model as a first order approximation. Koyama *et al.* (1994), however, indicated that the best fit linear trend of lateral displacement might include some significant discrepancy from that geological model, although this is left as a topic for further research.

Fig. 4. Estimated positions and their 1σ errors of Minami-torishima (see Fig. 1 for location) from 1989 to 1993 measured by the Western Pacific VLBI network. A straight line was fitted by using epoch values, which expresses the estimate of horizontal linear movement of the site (Koyama *et al.*, 1994).

3. Satellite Laser Ranging

Satellite Laser Ranging (SLR) has played an important role in the observation of geodynamic phenomena from space, by providing us with invaluable data especially related to the study of Earth rotation and global dynamics. SLR has also been applied to ocean dynamics through the tracking of altimeter satellites. These studies require acquisition of global satellite tracking data and precise data analyses. Therefore, major SLR projects have been performed as international cooperative programs.

In Japan, major activities have been lead by the Hydrographic Department of Japan (JHD), the Maritime Safety Agency, and the National Aerospace Laboratory (NAL), the Science and Technology Agency. The Communications Research Laboratory recently developed a new SLR system. The following sections describe their activities and discuss results.

3.1 SLR work at the Hydrographic Department

A Japanese experimental SLR system was developed in the late 1970s by JHD in cooperation with the Geographical Survey Institute (GSI) (Sasaki, 1977). The next system, which was installed at the Simosato Hydrographic Observatory, consists of a receiving telescope of 60 cm diameter and a YAG laser which transmits pulses of 150 mJ/shot and 200 pico-second(ps) width at a rate of 4 pulses-per-second(pps) (Sasaki *et al.*, 1983). After its completion in 1982, JHD started a project to determine the location of the mainland of Japan referred to a global geocentric coordinate system by SLR. The target satellites have been LAGEOS, STARLETTE, BEACON-C (untill mid-1986), AJISAI (from mid-1986), ERS-1 (from mid-1991), and TOPEX (from mid-1992). The range precision for these satellites was 10 cm level before July, 1990, when the laser transmitter was replaced by a new YAG laser with the capability of pulse transmission of 125 mJ/shot and 100 ps width at a rate of 4 pps. The range precision was improved to 6–7 cm.

The project has expanded to a geodetic control of all the major isolated islands in Japan. For this purpose, a transportable SLR station was developed in 1987 (Yamazaki and Mori, 1983; Sasaki, 1988; Sengoku, 1990). The transportable station, named HTLRS, has been shipped to several isolated islands twice a year on average since early 1988 (Kanazawa and Sengoku, 1989). The sites which HTLRS has occupied until 1993 are Chichi-jima, Ishigaki-jima, Minami-torishima, Okinawa Island, Tsu-shima, Oki Island, Minami-daito Island, Iwo Island, Hachijo Island, Tokachi and Wakkanai in Hokkaido (Fig. 1). The target satellites were LAGEOS, STARLETTE, and AJISAI and the range precisions for these satellites were 3–4 cm.

An orbital processor/analyzer has also been developed at JHD (Sasaki, 1981, 1984 a) based on linear estimation theory. The adopted dynamical system was the MERIT (Monitor Earth Rotation and Intercompare Techniques) Standards (Melbourne *et al.*, 1983). A set of station coordinates including Simosato, named JHDSC-1, was determined applying thus developed orbital processor/analyzer (Sasaki, 1984 b), which was completed in 1990 and named HYDRANGEA (HYdrographic Department RANGE data Analyzer) (Sasaki, 1990). The software is capable of estimating the satellite position and velocity at an instant of time, the Earth rotation parameters, station coordinates,

baseline lengths among stations, geophysical parameters such as the gravitational parameter (GM), the product of Newton's gravitational constant and the mass of the earth, and J_2 , the dynamical form factor, and satellite parameters such as the solar reflectivity coefficient, the air drag coefficient of the satellite. The precisions of the obtained baseline lengths of Simosato–Chichijima (938 km) and Simosato–Minamitorishima (2,025 km) determined by using HYDRANGEA attained 4 and 7 mm, respectively.

Sasaki *et al.* (1989) showed that a specific short arc method is extremely effective to determine baseline lengths, if SLR data are obtained simultaneously at multiple stations for successive passes of a satellite. The software developed by this method was named as SPORT (Successive Passes Orbit Revising Technique). The location of Ishigaki-jima was determined to a precision of 5 cm by employing a semi-long arc method which used four 5-day-arcs of LAGEOS (Sengoku, 1991). The pole position (x_p, y_p) and the excess rotation per day (dr) of the earth in 5 day intervals from September 1983 to October 1984 were estimated by means of 85 five-day-arcs of LAGEOS data. Comparing the results to those estimated at the Center for Space Research (CSR) of the University of Texas at Austin (Tapley *et al.*, 1986), the mean systematic differences for x_p, y_p , and dr were -0.51 mas, -0.13 mas, and -0.87 mas/day, respectively where 1 mas corresponds to approximately 3 cm on the earth's surface. The standard deviations of each five-day-result for x_p, y_p , and dr were 1.1 mas, 1.4 mas, and 0.42 mas/day, respectively.

Fig. 5. Change rates in the arc lengths on the Earth's surface derived from LAGEOS SLR data from 1984 to 1991. Units are cm/year. Negative value indicates contraction, while positive indicates extension. Values in parentheses are those by Minster-Jordan AM0-2 model.

Table 1. Change rates of arc lengths and direct baseline lengths by SLR observations and a plate motion model.

Baseline	Arc length		Baseline length	
	HDJ	M and J	NAL	M and J
Wettzel-Simosato	-3.6	0.0	-2.2	0.0
Matera-Simosato	-3.8	0.0	-0.7	0.0
Graz-Simosato	—	—	-0.9	0.0
Simosato-Yaragadee	-7.2	-7.7	-6.0	-6.5
Simosato-Hawaii	-8.1	-9.9	-5.4	-8.6
Simosato-Monument Pk.	-3.3	-6.4	-1.8	-4.8
Simosato-Quincy	+0.5	-19.0	+0.2	-0.9
Simosato-Arequipa	—	—	-0.5	-0.7
Hawaii-Yaragadee	-12.2	-10.3	-6.1	-6.7
Hawaii-Monument Pk.	+2.5	0.0	+1.9	0.0
Hawaii-Quincy	+2.6	+0.8	+2.3	+0.8
Yaragadee-Monument Pk.	-9.7	-10.3	-3.1	-3.9
Graz-Yaragadee	—	—	-1.1	-1.2
Hawaii-Arequipa	—	—	+5.5	+4.6
Arequipa-Yaragadee	—	—	+1.3	+2.3
Arequipa-Quincy	—	—	-0.2	-0.9
Quincy-Monument Pk.	-4.0	-5.3	-2.8	-5.3

HDJ, Hydrographic Department of Japan; NAL, National Aerospace Laboratory; M and J, Minster and Jordan (1978) model. Unit: cm/year.

The coordinates of worldwide SLR stations at epochs of 1984.80 (JHDSC-2), 1986.76 (JHDSC-3), 1988.11 (JHDSC-4), 1989.95 (JHDSC-5), and 1990.97 (JHDSC-6) were derived from LAGEOS data of 8 or 9 five-day-arcs for each epoch. The internal errors of the three dimensional rectangular coordinates, X , Y , and Z determined for the positions of 14 stations at 1984.80 were 2.6, 2.4, and 2.9 cm, respectively (Sasaki, 1990; Sasaki and Sengoku, 1993). Sengoku (1992) compared the station coordinates of JHDSC-2, 3, and 4 with other recent sets of station coordinates determined by the International Earth Rotation Service (IERS) (IERS, 1990) and found that the difference between these coordinates were at most 5 cm, after transformation.

Changes of arc lengths on the Earth's surface between SLR stations for the five epochs above are summarized in Fig. 5 and Table 1. Almost all the results are in good agreement with the AM0-2 model (Minster and Jordan, 1978). Simosato-Wettzel and Simosato-Matera, however, seem to show significant departure from the geological models. The changes in arc length for both of these baselines are estimated as about -3 cm (contraction) by the SLR data analysis although both stations are thought to lie on the Eurasian plate.

3.2 SLR research at the National Aerospace Laboratory

The National Aerospace Laboratory (NAL) has participated in the MERIT project as an analysis center for the SLR technique since 1983 (Murata, 1986 a, b, c). The MERIT main campaign was conducted for a period of 14 months between September 1983 and

October 1984 and was extended until January 1988 (MERIT extension) under the NASA's Crustal Dynamics Project (CDP) (NASA, 1980). NAL also participated in the CDP through the MERIT extension and performed analyses of SLR data for geodetic and geodynamic applications.

NAL developed an orbit processor, COSMOS, and used it for data analysis. The system is based on Bayesian least squares adjustment of tracking observations to a satellite orbit using a numerical integration method. It possesses a multi-arc processing capability. Models and constants of perturbation forces and kinematics adopted for LAGEOS data reduction adhered closely to the IERS Standards (see, for example, Murata, 1988 a, b). The results included two major solutions (Murata, 1993): a new set of global station coordinates; and a series of consecutive 1-year solutions, from which highly reliable and accurate contemporary plate motions were obtained.

In the first solution, the entire 7.3-year data span from September 1983 to December 1990 was used to determine a single set of geocentric coordinates of the laser stations and GM, simultaneously with orbit elements and earth orientation parameters. All the station positions were constrained to move according to the AM0-2 model. The positions have an epoch of 1988 January 1, 0h UTC. This solution for global station coordinates forms the basis for an initial definition of the terrestrial reference system at NAL (see, IERS, 1992).

In the second solution, in order to estimate tectonic plate motions from SLR data, station positions were adjusted using consecutive 1-year data intervals beginning in September 1983. The solution procedure was nominally the same as that used for the

Fig. 6. Change rates in the direct baseline lengths for the Circum-Pacific and global SLR networks. Minster-Jordan AM0-2 values in parentheses. Units are cm/yr. Refer Fig. 5 for sign.

above 7.3-year global analysis, except for the following two assumptions: Greenbelt and Arequipa were assumed to move according to the AM0-2 model; and GM was fixed to the new estimate of $398,600.4415 \text{ km}^3/\text{s}^2$ (Ries *et al.*, 1989). On the basis of these yearly determined coordinate solutions, the rates of change in baseline lengths are compared to the rates predicted by geological models such as AM0-2 or NNR-NUVEL1 (Argus and Gordon, 1991).

Figure 6 shows the estimated baseline length changes together with the AM0-2 model. Table 1 compares these results with those estimated by the Hydrographic Department (see the previous section). Note that the baseline lengths by JHD in the previous section are given as the arc lengths which are measured along the earth's surface, while those by NAL are the length of the direct straight line connecting two sites. Figure 7(a) shows the evolution of baseline length between Simosato and Haleakala, Hawaii. The best-fit slope for Simosato-Haleakala indicates $-5.4 \pm 0.6 \text{ cm/year}$ (contraction), whereas AM0-2 and NNR-NUVEL1 model suggest -8.6 cm/year and -7.7 cm/year , respectively. Figure 7(b) shows another example obtained for the baseline between Simosato and Yaragadee, Australia, which is either on the Indian plate (Minster and Jordan, 1978) or on the Australian plate (DeMets *et al.*, 1990). The estimated rate is $-6.0 \pm 0.5 \text{ cm/year}$. This rate is also in good agreement with -6.5 cm/year by the AM0-2 model and -6.7 cm/year by the NUVEL model.

The SAFE (San Andreas Fault Experiment) line consisting of Monument Peak on the Pacific plate and Quincy on the North American plate is worthy of special attention because it encompasses an active transform fault, the San Andreas fault. Monitoring of displacements on and around the fault is especially important to understand the tectonics at the transform plate boundary and for earthquake prediction studies in the area. The rate predicted by the AM0-2 model is -5.3 cm/year , whereas NUVEL model predicts -4.5 cm/year , assuming that the laser site at Monument Peak is lying on the Pacific plate. The present investigation resulted in a baseline change rate of -2.8 cm/year , which agrees quite well with the NASA estimate of $-2.6 \pm 0.2 \text{ cm/year}$. The discrepancy between the SLR results and geological models seems significant and might be attributed to the so called "San Andreas discrepancy" in which there is a significant discrepancy between geological slip rate of the San Andreas fault and the estimated plate motion between the North-American and the Pacific plates (e.g., Minster and Jordan, 1987). Although further discussion on this subject is outside of the scope of the present paper, we emphasize that close monitoring of the baseline length changes with SLR together with local surveys may provide extremely useful data to help us to understand the mechanism of the San Andreas discrepancy (Feigl *et al.*, 1993).

With regard to the rate of height components in Europe, it is of special interest that all European stations suggest subsidence, except for Matera and Zimmerwald. The Arequipa site, which is in south America, show subsidence. For the systematic trends observed for some other stations, further examination is clearly needed to confirm whether or not our results have tectonic significance.

In addition to these studies, the ETALON satellites, the former USSR's laser geodynamic satellite array composed of ETALON-1 and ETALON-2, were also used to evaluate their capability for scientific applications. Murata and Tsujii (1992) suggested that station coordinates, baselines, earth rotation parameters, and other geodetic

Fig. 7. (a) Baseline length difference from the Nominal Value between Simosato on EURA and Haleakala on PCFC. (b) Baseline length difference from the Nominal Value between Simosato on EURA and Yaragadee on INDI (the Indian plate).

Fig. 8. Position change of Ito site referenced to Hatsushima. Hatched portions are the period of the peak activity of the swarm. The arrow indicates the offshore eruption of July 10, 1989 (after Shimada *et al.*, 1990).

parameters are well determinable and comparable to existing solutions, in particular, to LAGEOS-1 solutions.

3.3 *SLR at the Communications Research Laboratory*

The Communications Research Laboratory (CRL) has developed a SLR system as one of the facilities in the Space Optical Communication Research Center in Tokyo (Kunimori *et al.*, 1991). It started observations of major geodetic satellites in January 1990. The system is equipped with a multi-purpose 1.5 m receiving telescope, 100 ps/100 mJ/10 Hz mode locked YAG laser and 3 cm precision receiver. The system will be used not only for geodetic measurements but also for optical time transfer experiments.

CRL has participated in the ETALON satellite tracking experiments from September to November, 1990. In this campaign, hundreds of thousands of range data over several tens of passes of ETALON-1, -2 and LAGEOS were obtained. Data analysis has been made employing data acquired at other stations, and the global position of the CRL SLR station has been determined with a precision of 5 cm. Since CRL has carried out regular international VLBI experiments from 1984, it is interesting to compare the coordinates of the SLR site with VLBI. A local survey has been made for the colocation of two techniques and confirmed an accuracy of about 10 cm in their respective site positions.

4. Global Positioning System

The largest difference of GPS from the former two techniques is that the ground systems are highly transportable and inexpensive. Thus the geodetic application of GPS has been of great interest among large number of geoscientists. In Japan, primary and fundamental research on GPS began around 1982. After the initial basic research, a large number of carrier phase differential GPS receivers were first introduced in 1987. Since then active surveys have been made in various areas and with different scales in Japan. This section introduces the major results from these campaigns. In order to exchange information and promote the research, a consortium was established among Japanese scientists and was named as the GPS Consortium of Japan. The consortium has organized a nationwide GPS campaign and domestic symposia (The GPS Consortium of Japan, 1989, 1990, 1991, 1993, 1995).

4.1 *Continuous tracking network*

Since most of GPS observation systems were introduced under the national research program for earthquake prediction, GPS research has chiefly been focused on delineating crustal deformation. For such an objective, the telecommunication system is indispensable for acquiring data as rapidly as possible. Among various networks, the National Institute for the Earth and Disaster Prevention (NIED) first established a continuous monitoring network in the south Kanto and the Tokai area with more than 10 stations (Shimada *et al.*, 1989).

The first significant baseline change was found on the occasion of the Off-Ito swarm-volcanic activity in 1989. Along with the largest shock which registered $M 5.5$,

Fig. 9. Satellite tracking network by the Geographical Survey Institute (after Tsuji, 1992).

a considerable baseline vector change was observed (Fig. 8; see Shimada *et al.*, 1990). Okada and Yamamoto (1991) used GPS data together with other geodetic data to interpret the seismo-volcanic process occurred in the area with an open crack model. Extensive study of 16 months of data from the network by Shimada and Bock (1992) has shown the westward migration of the Izu Peninsula.

University groups including Tohoku, Tokyo, Nagoya, and Kyoto Universities have also established individual continuous monitoring networks at respective areas. Hydrographic Department, Maritime Safety Agency, also deployed three stations around Sagami Bay. Results from these networks are periodically reported at the meeting of the committee for the earthquake prediction (e.g., Earthquake Research Institute *et al.*, 1991; Disaster Prevention Research Institute, 1993; Hydrographic Department, 1991).

The Geographical Survey Institute (GSI) first established a local continuous monitoring network around the Ito region since 1990 to monitor seismo-volcanic activity in the region (GSI, 1990). Since 1994, GSI began to introduce a nation-wide GPS continuous monitoring network with more than 100 sites to monitor crustal strain in the Japanese islands since 1994 (Abe and Tsuji, 1994). The network will be augmented to more than 600 in 1996 (GSI, personal communication).

Recognizing the importance of precise orbits for better baseline estimates, GSI has established a domestic satellite tracking network. The network consists of four stations; namely Shintotsukawa, Tsukuba, Chichi-jima, and Kanoya (see Fig. 9; Tsuji, 1992). These stations employ dual frequency receivers and tracks satellites nearly 24 h a day. The system, now operational, was implemented to produce post-processed ephemeris with positioning accuracies of better than 0.1ppm (Tsuji, 1992). The primary station of the network, Tsukuba, is also a site for a global tracking network, Cooperative

Fig. 10. Regional GPS networks in Japan and their results. (a) Network at the Sagami-Bay area and displacement vectors obtained from the 1989–1990 GPS measurements (after Chen and Kato, 1992), (b) network at Shikoku and principal strains deduced from 2 years of observation (after Tabei *et al.*, 1991), and (c) network in the south-western islands and comparison of the measured (solid) and predicted (dashed) plate motions (Hirahara *et al.*, 1992).

International GPS NETWORK (CIGNET), operated by the National Geodetic Survey (NGS), USA. Thus, the tracking schedule is synchronized with the CIGNET tracking schedule. The estimated orbits from this network are now available to Japanese local geodetic users upon request.

CRL independently developed a new differential GPS receiver called PRESTAR (PRECise SATellite Ranging). It employs a microstrip array antenna which is directed to a satellite under the control of a micro computer. A rubidium oscillator is employed for a highly stable reference signal (Sugimoto *et al.*, 1989). Sugimoto *et al.* (1989) made an experimental observation using PRESTAR at the Tsukuba baseline which has well been established by VLBI. The difference of baseline lengths between VLBI and GPS was about 3 cm.

4.2 Major field experiments

Based on the objective of detecting crustal deformation by GPS, research groups of university scientists have deployed several local and regional experiments. Some of their results are shown in Fig. 10.

The first project that the university group tackled is the establishment of a local dense network in the south Kanto area, where a large earthquake is hypothesized in

Table 2. Institutions that have participated in GPS JAPAN project.

Hokkaido University	Nagoya University
Hirosaki University	Gifu University
Tohoku University	Kyoto University (SCI)
Ibaraki University	Kyoto University (DPRI)
Chiba University	Kochi University
Tokyo University (SCI)	Fukuoka Kyoiku University
Tokyo University (ERI)	Kyushu University
Shizuoka University	Ryukyu University
Shinshu University	Tokai University
Toyama University	Kyushu Tokai University
Kanazawa University	
National Astronomical Observatory (Mizusawa)	
National Astronomical Observatory (Nobeyama)	
National Research Institute for Earth Science and Disaster Prevention	
Geographical Survey Institute	
Meteorological Institute	
Communications Research Laboratory	
Maritime Safety Agency (Hydrographic Department)	
Maritime Safety Agency (Maritime Safety Academy)	
National Aerospace Laboratory	
Japan Marine Science and Technology Center	
Geological Survey of Japan	
Hot Springs Research Institute, Kanagawa Prefecture	

the near future (e.g., Ishibashi, 1988a, b). The project was initiated in 1988, and the first experiment was made in December of the same year and has been repeated once a year at nearly the same season (Murata *et al.*, 1990). Ten university departments have participated in the campaign. Figure 10(a) shows the network in 1991 and the displacement vectors from the partial network using WM102 dual frequency receivers. The station distribution is primarily unchanged but there have been slight changes from year to year. Baseline length change rates estimated from the linear regression of the 2 years of data are used for this analysis (Chen and Kato, 1992). Although it still seems premature to discuss crustal deformation, the strain changes seem more or less reasonable compared with other results (Kimata *et al.*, 1991; Shimada and Bock, 1992).

Tabei *et al.* (1991) demonstrated that the principal strains in the Shikoku region deduced from 1990 and 1991 GPS observation were consistent with conventional geodetic surveys (Fig. 10(b)). Also, Hirahara *et al.* (1992) delineated the plate motion between the Philippine Sea plate and the Eurasian plate by 2 years of GPS observation at three islands in the southwestern islands of Japan (Fig. 10(c)). The results show good agreement with plate motions determined by other methods (e.g., Seno, 1977). As the data accumulate, these kinds of results will accumulate and it will be possible to discuss crustal strain in more detail in the near future.

4.3 "GPS JAPAN" project

In order to integrate the numerous projects that are being undertaken among

various universities and national institutes, the GPS Consortium of Japan has organized a nationwide campaign named "GPS JAPAN" (Kato, 1990). The chief objectives of the campaign are as follows: (1) Evaluation and improvement of the GPS baseline estimates employing post fit precise orbits, (2) Colocation of GPS sites to VLBI and SLR sites to obtain accurate site locations in the IERS Terrestrial Reference Frame, (3) Establishment of a nationwide GPS network for future tectonic studies.

It is apparent that this kind of nationwide project demonstrates the possibility of a more efficient and interdisciplinary approach of GPS studies for covering a wide area of geodesy and geophysics in the western Pacific region.

The "GPS JAPAN" experiments have been repeated five times in 1990, 1991, 1992, 1993, and 1994. More than 100 people from more than 30 universities and public institutes participated in the campaign (Table 2). And more than 80 dual frequency receivers were used.

Moreover, a number of foreign sites in the surrounding countries were able to participate in the campaign; they are, Wuhan in China, Daejeon in Korea, several stations in Chinese Taiwan and Guam. Figure 11 shows the station distribution at the time of 1991 experiment. The station configuration in the 1990 and 1992 experiments was nearly the same. Since the station distribution encompassed all of eastern Asia and the Philippine Sea plate, the future repetitions of the campaign may delineate regional

Fig. 11. Station distribution of the GPS JAPAN '91 campaign.

crustal deformations including the relative plate motions, in much more detail than has previously been possible.

The acquired data have been archived at a temporary data center located at the Earthquake Research Institute, the University of Tokyo. Magneto-Optical discs on the PC are used for this purpose. In order to tie GPS stations with other astrogeodetic sites, almost all VLBI/SLR sites have been occupied during the campaign. Although careful local ground ties should be made, the GPS station coordinates will thus be connected to a more accurate terrestrial reference frame in the near future.

4.4 *Regional contribution to the International GPS Service for Geodynamics*

Recognizing the importance of world coordination for the full realization of GPS potential capabilities and to support the development of geodesy and geophysics in general, the International Association of Geodesy (IAG) advocates the continuation of the International GPS Service for Geodynamics (IGS) as an international permanent voluntary organization.

The primary objective of IGS is to support world geodetic and geophysical research through providing GPS products such as precise orbits and Earth rotation parameters (e.g., Kato, 1992). However, the products themselves include invaluable scientific achievements such as: realization of a precise Global Terrestrial Reference Frame, precise determination of Earth rotation parameters, and so on (IAG, 1991; see also National Research Council, 1991). It also supports local and regional geodynamic studies and scientific orbital missions through determination of precise GPS orbits. Further geophysical applications such as monitorings of global sea-level change, post-glacial rebound, and local crustal deformations for earthquake prediction may be anticipated.

Aiming at the regular operation of the organization in 1994, an IGS oversight committee was organized at the IUGG conference that was held in Vienna in 1991. The committee first coordinated a world campaign in 1992 to examine the feasibility of worldwide coordination and data flow for the regular operation of IGS. The campaign was undertaken from June 21 to September 23 of 1992 (Campaign '92) with a core period of July 25 to August 8 (Epoch '92). During the Campaign '92, the world core sites of more than 30 stations were used to track satellites continuously. In the Epoch '92 period, far more sites were occupied to augment sites over the world, so that the network becomes dense enough to apply to the regional scale research.

The campaign proceeded smoothly. The campaign was first extended to the end of October and, then, was taken over by the pre-operational PILOT Service toward the real operational stage. And finally, IGS activity became operational starting in January, 1994, as was previously expected. Murata *et al.* (1993) used data for 19 global sites from the Epoch '92 campaign to estimate a number of parameters such as satellite orbits, pole positions, site coordinates, etc. Obtained orbit repeatability was mostly 10 m or less with some exceptions. Comparison of orbits with otherwise estimated ones at the Center for Orbit Determination (CODE) of Bern University showed overall agreement at a level of better than 5 m in rms. Day-to-day repeatability of baseline lengths was a few parts in 10^8 for baselines up to 12,000 km.

In the western Pacific region, the GPS Consortium of Japan coordinated a regional

Fig. 12. Network for IGS '92/Epoch '92 campaign in the western Pacific region (WING '92).

international campaign in parallel with Epoch '92. This regional campaign was named the Western Pacific Integrated Network of GPS (WING '92/IGS '92) (Fig. 12). As is readily seen, the station distribution is similar to the international part of the GPS JAPAN project. Through this kind of international cooperation, the Japanese GPS activity could contribute to the users in the eastern Asia, where modern geodetic work, including detailed mapping, is clearly needed, through distributing more precise orbits over the region by incorporating sites in the western Pacific area. Moreover, long term cooperative observations in this region will lead us to a further understanding of tectonics in eastern Asia, where complicated tectonic processes are taking place.

WING '92 campaign was a first trial to conduct a regional campaign in parallel with a world campaign. To make the data and information flow smoothly, the Earthquake Research Institute established the GPS Data and Information Center (GDIC) which is an expansion of the GPS temporary data center that was established for the GPS JAPAN campaign. GDIC used the INTERNET worldwide communication link so that it could acquire all world core sites data without any delay. In addition, GDIC accumulated the data collected at the WING campaign. All data were converted into the standard RINEX format (Gurtner and Mader, 1990), and were stored in an on-line disc that any user can access. These campaign data are now being used for further analyses.

5. Discussion

Application of space techniques by Japanese scientists has provided various results

for global and regional studies on tectonics. First of all, the consistency of relative plate motions derived from VLBI and SLR techniques with the RM-2 model (Minster and Jordan, 1978) or NUVEL-1 model (DeMets *et al.*, 1990) should be emphasized. The constant rate of the change in baseline lengths seen in Fig. 2 strongly suggests the steadiness of relative plate motion. In other words, the plates move without any short period undulation, rather they move very steadily even on a temporal scale of a few years. SLR data (Figs. 5, 6 or Table 1) also suggest that the change rates of baseline lengths show good consistency with a plate motion model such as AM0-2 as the first order approximation. The next question is whether such linear displacement is due to the ultimate rigidity of the plate. Since the Japanese islands are located at a converging plate boundary where rather complex internal deformation is anticipated, the monitoring of deformation in Japan will clarify the behavior and properties of the lithosphere at such converging boundaries.

Generally speaking, the displacements of a site may be assumed as the sum of the rigid, elastic and non-elastic components as follows:

$$v = v_r + v_e + v_n,$$

where v is the observed velocity vector of the site; v_r is the rigid component, v_e is the elastic component, and v_n is the non-elastic component, respectively. The rigid component v_r might be thought of as linear with time as the average uniform displacement over the entire plate. Within a stable continent or in the middle of an oceanic plate, the other two components might be relatively small compared to the first one. However, in a tectonically active area such as Japan, non-rigid components may not be negligible. Therefore, we need to distinguish v_e and v_n from v_r in such areas.

Heki *et al.* (1990), for example, indicated westward migration of Kashima which could be attributed to crustal shortening due to the compression caused by the Pacific plate in the North-American or Eurasian plates. Similar landward displacement is seen at Simosato by SLR observation. Sasaki (1990) suggested that the contraction between Simosato and European sites of about 3 cm/year might be due to the compression of the Philippine Sea plate toward the Japanese Islands at the Nankai trough, 100 km southeast from Simosato, to northwest in the rate of 4 cm/year (e.g., Seno, 1977). Harrison and Douglas (1990) obtained similar results. The height component of SLR results at Simosato station shows uplift at a uniform rate of 11 mm/year, which is, however, contradictory with the uplift rate of 1–2 mm/year estimated from the long term (>30 years) record of sea level nearby (Kato, 1983). Although further research is needed to clarify the causes of these deformations, these lines of evidence suggest that local deformation studies are indispensable for global dynamics studies based on either VLBI or SLR observations, because many of these sites are located in tectonically active areas.

Non-rigid motions, v_e and v_n , may be manifested mainly as non-uniform motions of the plate. Observation of such non-uniform displacements—either temporally or spatially—may provide us with further detailed information to help understand the mechanism of strain in the crust and the upper mantle, especially at plate boundaries. Kimata (1992), for example, found a strain episode in the Tokai region which lasted

from 1985 to 1987. Such local and temporal deformations are also widely seen in volcanic areas in Japan.

In order to separate these non-rigid motions from rigid plate-scale motions, we need to monitor local crustal deformation at and around the global VLBI/SLR sites. For this purpose, GPS may play an important role. Close ground ties of reference points among different techniques and full knowledge of precise transformation parameters between different reference frames are indispensable to unify the results. Although global efforts such as IERS or IGS may be crucial to solve this problem, regional efforts such as in the western Pacific can significantly contribute to improving the regional and thus global accuracy of the terrestrial reference frame.

Finally, we would like to point out that once we understand the process and mechanism of crustal strain in and around Japan through these space techniques, we can further discuss the process of earthquake generation. This kind of approach may facilitate long term earthquake prediction research, and the continuous monitoring of deformation will open a new approach for shorter term earthquake prediction as well.

6. Summary and Concluding Remarks

Japanese activities of application of space techniques have been briefly reviewed in this article.

First of all, the Japanese VLBI system has mostly been developed by the CRL and the joint efforts of CRL with GSI and NAO provide invaluable geodetic data. We note that the domestic VLBI network is important to delineate the entire framework of deformation of the island arc in relation to global dynamics. Further coordination may be needed for more systematic and efficient geodetic work.

SLR for geodetic and geodynamic purposes was started by JHD in Japan. The fixed station at Simosato is part of the world SLR network. HTLRS, a mobile SLR station, was developed at JHD and has been used extensively around Japan to estimate the accurate position of remote islands of Japan. Data analyses have also been made by JHD and NAL using global data. The results were in good agreement with RM-2 or NUVEL-1 geological plate motion models in the sense of a first order approximation. A closer look, however, indicates significant departures from a simple rigid model. Although we can attribute such non-rigid component of deformation to the non-rigid behavior at converging plate boundary, further data are clearly needed.

Finally, GPS research activities have been documented. The major objective of GPS application in Japan is to detect and monitor the crustal strain in and around Japan closely, which will provide us with invaluable data for long term earthquake prediction.

The ultimate goal in combining these techniques is to define and monitor the figure of the globe and its deformation. An interdisciplinary approach and cross organizational cooperation are now truly necessary for this purpose. Such national activities should be oriented to contribute to global activities such as IERS or IGS. Unification of global, regional, and local scale studies by the space techniques will lead us to revolutionary developments in geodesy and geophysics.

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