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Report of the Geodetic Works in Japan for the Period January 2003 to December 2006

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THE GEODETIC SOCIETY OF JAPAN

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1. Introduction

This report summarizes the geodetic activities in Japan for the period from January 2003 to December 2006. It is to be submitted, on behalf of the Geodetic Society of Japan (GSJ), to the XXIV General Assembly of the International Union of Geodesy and Geophysics (IUGG) to be held in Perugia, Italy, July 2007.

During this four years period, GSJ, together with the Science Council of Japan and 15 other learning societies in Japan, hosted the IUGG XXIII General Assembly in Sapporo in 2003. More than 4600 researchers from about 80 countries and regions attended the Assembly and a number of outreach programs for the public were intensively undertaken in Sapporo and its surrounding areas. GSJ was deeply involved with two programs. The first program consisted of two public lectures. Prof. Shuzo Takemoto, Kyoto University, delivered the first lecture on global changes as detected by satellites and recent surface observation techniques such as gravity meters, extensometers and tiltmeters, while Prof. Erwin Groten from Germany delivered the second lecture on remarkable advancement of the recent space-borne observation techniques. The second program was aimed at inspiring and motivating the interest of school children in science. As a result, the program was especially organized at an elementary school in Sapporo. Prof. James E. Faller from the United States of America provided a lesson on measurement of gravity and Prof. Shuhei Okubo, University of Tokyo on volcanoes and gravity.

GSJ holds scientific meetings twice a year and a tutorial summer school for young geodesists annually. In addition, GSJ awards the Tsuboi Prize to a young geodesist for his/her significant contributions to geodetic science and the Group Tsuboi Prize to a group of geodesists for their joint contributions every year. In the past four years, Drs. K. Matsumoto, T. Otsubo, Y. Hatanaka and S. Miyazaki were the winners of the Tsuboi Prize, and the GEONET Group of the Geographical Survey Institute (GSI) represented by Y. Kumaki, the Gravity Research Group in Southwest Japan represented by R. Schichi and A. Yamamoto, the Satellite Laser Ranging Research Group of the Japan Coast Guard (JCG) represented by M. Sasaki, and GSI and Hydrographic and Oceanographic Department, JCG (JHOD) represented by M. Murakami and A. Sengoku, respectively, were the awardees for the Group Tsuboi Prize. GSJ also celebrates the best presentation student awards at its fall meeting. K. Yamamoto, M. Irwin, I. Hirose, Y. Kobayashi, K. Takatani, Y. Fukushima, H. Takiguchi, T. Kazama, S. Yui, R. Ogawa, and S. Yoshii were the recipients of the best presentation awards in the last four years.

In 2004, GSJ celebrated its fiftieth anniversary. As part of the commemorative activities, GSJ published two books in Japanese: an introductory book on geodesy for the general public (Okubo ed., 2004) and a CD-ROM textbook on geodesy for researchers and university students (Geodetic Society of Japan, 2004).

During the period 2003 to 2006 a variety of geodetic activities have been undertaken in Japan. We may name some major ones out of them. In August 2003, the first absolute gravity measurement was successfully made on the top of Mt. Fuji (at elevation of about 3800 m).

The Japanese continuous GPS observation network called the GPS Earth Observation Network System (GEONET) has been reinforced in both qualitatively and quantitatively. The number of continuous sites grew up to about 1200, and the acquired data are transferred on a real time basis. Analysis strategy has been updated to realize a better accuracy. GEONET, the world's largest regional GPS network, is serving for not only geodesy but also various subjects in Earth science.

Another new important geodetic facility to be noted is the Advanced Land Observing Satellite (ALOS) "Daichi", which was successfully launched in January 2006. The satellite is equipped with the L-band Synthetic Aperture Rader (SAR) sensor and can be used to monitor changes in the deformation of the surface regardless of vegetation.

International geodetic activities have also been made intensively. In addition to the continued work under the Global Geodynamics Project (GGP) that was initiated as an international project during the period described in the previous national report, the Absolute Gravity Standard Station Network in East and South-East Asia has been established as a part of the Asia-Pacific Space Geodynamics Project cooperation campaigns in the International Association of Geodesy (IAG) and the Permanent Committee on GIS Infrastructure for Asia and the Pacific (PCGIAP). A joint team of Japanese and U.S. researchers has begun a four year project of integrated geodetic observation in 2005, called International geodetic project on South Eastern Alaska, for detecting the crustal deformation and studying the viscoelastic structure of the Earth in that area.

During those four years, there occurred many significant geophysical events such as the 2004 Sumatra-Andaman earthquake. In Japan, the 2003 Tokachi-oki earthquake was the first M8 interplate earthquake after the installation of dense nationwide geophysical monitoring systems. Thorough analyses of multi-disciplinary data have been conducted to reveal unprecedented details of this typical plate boundary earthquake.

Technological development in geodetic measurements now opens a new stage toward better understanding of the Earth's figure, internal structure and dynamics, and their temporal evolution. More and more new findings are anticipated in the next several years.

Bibliography

Geodetic Society of Japan (2004): Commemorative CD-ROM Textbook on Geodesy for the fiftieth anniversary of Geod. Soc. Japan. (in Japanese)
Also found at http://wwwsoc.nii.ac.jp/geod-soc/web-text/index.html

Okubo, S. (ed.) (2004): Chikyu ga Maruitte Honto Desu ka ? (Is the Earth Really Round ?) ~ 50 Questions to Geodesists, Asahi Sensho 752, Asahi Shimbun-sha, 278p. (in Japanese)

2. Positioning

2.1 Single Technique

GSI has been operating the Tsukuba 32-m Very Long Baseline Interferometry (VLBI) station (TSUKUB32) and the Tsukuba VLBI Correlator Facility to participate in the international 24-hour sessions that are carried out as a collaborative program organized by the International VLBI Service for Geodesy and Astrometry (IVS). One of the major tasks assigned to GSI is the observation using the 32-m-diameter antenna and the data processing for the sessions (IVS-INT02) over the baseline between TSUKUB32 – WETTZELL (Germany) baseline for the purpose of monitoring UT1-UTC. GSI has also conducted geodetic VLBI sessions with a domestic VLBI network in order to control and monitor the consistency of the Geodetic Reference System of Japan. Fujisaku et al. (2005), Fujisaku et al. (2006), Kokado et al. (2006), Kurihara et al. (2003), Machida et al. (2004), Machida et al. (2005), Machida et al. (2006), Miyagawa and Kurihara (2003), Takashima et al. (2005), Takashima et al. (2006a) and Takashima et al. (2006b) reported those activities.

GSI repeated precise leveling surveys in Tokai and South Kanto Regions. It also carried out precise leveling and GPS surveys in Muroto and Kii areas to monitor interseismic deformations of Tonankai and Nankai earthquakes.

GSI also carried out oversea GPS measurements between Japan and Republic of Korea. Yokokawa et al. (2004) concluded that the difference of the relative coordinates between Japan and Korea given by the old Tokyo Datum System and GPS measurements was about 40 cm. For this comparison they used the precise GPS measurement results obtained as a collaborative project between GSI and National Geographic Information Institute, South Korea.

JHOD has been conducting continuous GPS observation at 39 onshore GPS stations for monitoring crustal deformation (Hydrographic and Oceanographic Department, 2003a; 2003b; 2004; 2005; 2006). They improved their continuous GPS observation system in 2004 (Fuchinoue et al., 2005). Besides continuous observation, they carried out campaign observations on Zeni Su, in the vicinity of Izu Islands in 2003, 2004 and 2005 (Hydrographic and Oceanographic Department, 2004; 2005; 2006).

Shibuya et al. (2003) summarized progress of geodetic observations at Syowa Station in recent 10 years. Shibuya et al. (2005) also summarized location coordinates of geodetic sensors at Syowa Station. Jike et al. (2005) determined station coordinates from the first year observation of Antarctic VLBI. Doi et al. (2004) carried out GPS observations at three points on Antarctic ice sheet, and determined their coordinates and velocities.

The Geological Survey of Japan and National Institute of Advanced Industrial Science and Technology (GSJ/AIST) established GPS array in and around Kinki District (Ohtani et al., 2003).

2.2 Multiple Techniques

GSI contributed to the adoption of the Japanese New Geodetic Datum 2000 (JGD2000), which was made effective by amendment of the Japanese Survey Act in the national parliament in 2002, through providing backup and supporting work forces together with JHOD. The tasks included intensive studies on the theoretical background of the reference frame, recalculation of the positions horizontal reference points and vertical benchmarks, negotiations with local and municipal governments, and public communications.

Tobita et al. (2003) calculated and compiled datum conversion vectors for 57 Japanese islands to translate coordinates from the old Tokyo Datum system to the new Datum, which is consistent with the International Terrestrial Reference Frame (ITRF). Tsuji and Matsuzaka (2004) reviewed the procedures taken by the GSI to accomplish the establishment of horizontal part of the new system, which included the calculation of the new coordinates of horizontal control points including VLBI and GPS permanent stations. Imakiire and Hakoiwa (2004) reviewed the construction of the new height system highlighting the procedures of the calculation of the new vertical coordinates including islands. Matsumura et al. (2004) described the framework of the new geodetic reference system of Japan adopted in 2002 including basics concepts of the new system and reformations made in related legislature. GSI (2004) described impacts of adoption of the new geodetic datum of Japan on the survey community and downstream influences on other social sectors.

Masaki et al. (2006) determined the local-tie translation parameters between the GPS (S003; CCJM) and VLBI (S005; VERA-Ogasawara) antennae at Chichijima (DOMES site number 21732) using relative positions derived from their on-site survey. They also reported results of error budgets in their analysis. They concluded that more precise GPS survey was necessary to achieve further accuracy in local tie parameters.

GSI conducted various surveys to maintain the national geodetic frame to accommodate permanent crustal deformations caused by the seismic and volcanic events. GSI carried out surveys over the areas affected by the 2003 Tokachi-oki, the 2004 Mid Niigata Prefecture and the 2005 Fukuoka-ken Seiho-oki earthquakes (e.g. Tsuji et al., 2004; Numakawa et al., 2003). Doi et al. (2005) reported the processes of revision of the coordinates for a total of 6700 survey stations (continuous GPS, horizontal and vertical) to remedy the permanent crustal deformations due to the 2003 Tokachi-oki earthquake.

Sato et al. (2004) presented horizontal motions of four mobile SLR stations and showed that all of them were consistent with the results derived from GPS and VLBI observation by GSI.

Bibliography

Doi, K., N. Imae, N. Iwata, and N. Seo (2004): GPS observations on the Antarctic ice sheet conducted during JARE-41, Antarctic Record, **48**, 7-18. (in Japanese with English abstract)

Doi, H., Y. Shirai, M. Ohtaki, T. Saito, T. Minato, H. Chiba, T. Inoue, K. Sumiya, J. Sugawara, Y. Tanaka, H. Saita, T. Yahagi, H. Kojima, T. Yutsudo, T. Amagai, and M. Iwata (2005): The Revision of Geodetic Coordinates of Control Points Associated with the Tokachi-oki Earthquake in 2003, J. Geogr. Surv. Inst., **108**, 1-10.

Fuchinoue, H., K. Kawai, and M. Fujita (2005): Continuous GPS observation by Japan Coast Guard – A new system for automatic data download and analysis -, Tech. Bull. Hydrogr. Oceanogr., **23**, 61-65. (in Japanese)

Fujisaku, J., S. Kurihara, and K. Takashima (2005): Tsukuba 32-m VLBI station, in D. Behrend and K. D. Baver (eds.), IVS 2004 Annual Rep., NASA/TP-2005-212772, 115-118.

Fujisaku, J., K. Kokado, and K. Takashima (2006): Tsukuba 32-m VLBI station, in D. Behrend and K. D. Baver (eds.), IVS 2005 Annual Rep., NASA/TP-2006-214136, 133-136.

Hydrographic and Oceanographic Department (2003a): DATA Rep. Hydrogr. Oceanogr. Observ., Ser. Satellite Geod., **15**. (in Japanese) (http://www1.kaiho.mlit.go.jp/jhd-E.html)

Hydrographic and Oceanographic Department (2003b): DATA Rep. Hydrogr. Oceanogr. Observ., Ser. Satellite Geod., **16**. (in Japanese) (http://www1.kaiho.mlit.go.jp/jhd-E.html)

Hydrographic and Oceanographic Department (2004): DATA Rep. Hydrogr. Oceanogr. Observ., Ser. Satellite Geod., **17**. (in Japanese) (http://www1.kaiho.mlit.go.jp/jhd-E.html)

Hydrographic and Oceanographic Department (2005): DATA Rep. Hydrogr. Oceanogr. Observ., Ser. Satellite Geod., **18**. (in Japanese) (http://www1.kaiho.mlit.go.jp/jhd-E.html)

Hydrographic and Oceanographic Department (2006): DATA Rep. Hydrogr. Oceanogr. Observ., Ser. Satellite Geod., **19**. (in Japanese) (http://www1.kaiho.mlit.go.jp/jhd-E.html)

Imakiire, T. and E. Hakoiwa (2004): JGD2000 (vertical) -The New Height System of Japan-, Bull. Geogr. Surv. Inst., **51**, 31-51.

Jike, T., Y. Fukuzaki, K. Shibuya, K. Doi, S. Manabe, D. Jauncey, G. Nicolson, and P. McCulloch (2005): The first year of Antarctic VLBI observations, Polar Geosci., **18**, 26-40.

Kokado, K., M. Machida, and K. Takashima (2006): High precision determination of earth orientation parameter by VLBI global solutions, J. Geogr. Surv. Inst., **110**, 11-25. (in Japanese, in press)

Kurihara, S., K. Takashima, T. Tanabe, H. Kawawa, and K. Miyagawa (2003): IVS Intensive VLBI Experiments for UT1 determination between Tsukuba and Wettzell, J. Geogr. Surv. Inst., **102**, 3-10. (in Japanese)

Machida, M., M. Ishimoto, S. Kurihara, and K. Takashima (2004): Tsukuba VLBI Correlator, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2003 Annual Rep., NASA/TP-2004-212254, 136-139.

Machida, M., M. Ishimoto, S. Kurihara, and K. Takashima (2005): Tsukuba VLBI Correlator, in D. Behrend and K. D. Baver (eds.), IVS 2004 Annual Rep., NASA/TP-2005-212772, 162-165.

Machida, M., M. Ishimoto, K. Takashima, T. Kondo, and Y. Koyama (2006): K5/VSSP data processing system of small cluster computing at Tsukuba VLBI Correlator, in D. Behrend and K. D. Baver (eds.), IVS 2006 General Meeting Proc., NASA/CP-2006-214140, 117-126.

Masaki, Y., S. Matsuzaka, and Y. Tamura (2006): Local Tie Survey at VERA Ogasawara Station at Site Chichijima, in D. Behrend and K. D. Baver (eds.), IVS 2006 General Meeting Proc., NASA/CP-2006-214140, 366-370.

Matsumura, S., Msk. Murakami, and T. Imakiire (2004): Concept of the New Japanese Geodetic System, Bull. Geogr. Surv. Inst., **51**, 1-9.

Miyagawa, K. and S. Kurihara (2003): Tsukuba VLBI Correlator, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2002 Annual Rep., NASA/TP-2003-211619, 197-200.

Numakawa, K., Y. Hirai, Y. Shirai, H. Shimo, K. Nemoto, M. Ohtaki, H. Doi, T. Saitou, H. Shinno, T. Minato, S. Tanoue, M. Tokudome, J. Sugawara, H. Kawawa, Y. Takashima, and S. Kurihara (2003): Tsukuba 32-m VLBI station, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2002 Annual Rep., NASA/TP-2003-211619, 157-160.

Ohtani, R., N. Matsumoto, N. Koizumi, M. Takahashi, T. Sato, Y. Kitagawa, E. Tsukuda, T. Satoh, H. Ito, and Y. Kuwahara (2003): The continuous GPS array observation by the Geological Survey of Japan, AIST, Bull. Geol. Surv. Japan, **54**(5/6), 193 - 212.

Sato, M., H. Fukura, and M. Fujita (2004): Horizontal motions derived from satellite laser ranging observations, Rep. Hydrogr. Oceanogr. Res., **40**, 73-84. (in Japanese with English abstract)

Shibuya K., K. Doi, and S. Aoki (2003): Ten years' progress of Syowa Station, Antarctica, as a global geodesy network site, Polar Geosci., **16**, 29-52.

Shibuya, K., K. Doi, Y. Fukuzaki, and M. Iwata (2005): Geodesy reference points within Syowa Station, Antarcica, and their local geodetic ties, Polar Geosci., **18**, 130-161.

Takashima, K. (2006a): Open house of VLBI facility and PR technique, VLBI Conf. Symp. 2005 Proc., 124-127. (in Japanese)

Takashima, K. (2006b): International observations of VLBI in GSI, Tech. Rep. Geogr. Surv. Inst., **A1-313**, 13-22. (in Japanese)

Takashima, K., M. Ishimoto, M. Machida, J. Fujisaku, and S. Kurihara (2005): The practical operation of eVLBI session to obtain UT1 solution rapidly, in M. Honma (ed.), VLBI Conf. Symp. 2004 Proc., 102-103. (in Japanese)

Tanaka, K., Sumiya, T. Inoue, K. Chiba, A. Yamada, K. Iwata, S. Chida, H. Saita, I. Saitou, J. Itou, and M. Yamanaka (2004): Responses of Geodetic Department of GSI to the Mid Niigata Prefecture Earthquake in 2004, J. Geogr. Surv. Inst., **107**, 35-44. (in Japanese)

Tobita M., H. Tsuji, Y. Takahashi, and T. Kawahara (2003): Correction Vectors for Island Positions in Tokyo Datum, J. Geod. Soc. Japan, **49**, 181-192. (in Japanese with English abstract)

Tsuji, H. and S. Matsuzaka (2004): Realization of Horizontal Geodetic Coordinates 2000, Bull.

Geogr. Surv. Inst., **51**, 11-30.
Tsuji, H., Y. Shirai, M. Ohtaki, K. Sugihara, R. Kawamoto, I. Kimura, and T. Inoue (2004): The Response of the Geodetic Department of GSI to the Tokachi-oki Earthquake in 2003, J. Geogr. Surv. Inst., **105**, 3-15. (in Japanese)
Yokokawa, K., S. Tanoue, K. An, and J. Park (2004): Joint Re-measurement of Japan-Korea Connecting Triangulation Network by GPS, J. Geogr. Surv. Inst., **103**, 63-72. (in Japanese)

3. Development in Technology

3.1 VLBI

In the past, the VLBI technique was severely hampered because the data had to be recorded onto tape and then shipped to a central processing facility for analysis. However, a standard personal computer (PC), hard drive-based storage, and advanced networks are now making the real-time electronic transmission of VLBI data a reality (Kondo, 2005). The e-VLBI technique has enabled us to perform software-based correlation processing using PCs (Kondo et al., 2003; Kondo et al., 2004; Kondo et al, 2006). Kondo et al. (2004) presented K5 VLBI system equipped with a PCI-bus Versatile Scientific Sampling Processor (VSSP) board (K5/VSSP). The K5/VSSP system is compatible with the former tape-based VLBI system and it is the multiple PC-based VLBI system on the FreeBSD and Linux operating system. The K5/VSSP system also includes the original software packages for data sampling and acquisition, real-time IP data transmission, and correlation analysis.

Kimura et al. (2003) developed another PC-based K5 system, which is called "K5/PC-VSI system". The K5/PC-VSI system consists of a high performance PC equipped with a specific PCI-bus board for data acquisition, raid data storage, and a gigabit class A/D sampler (Kimura et al., 2004). The PCI-bus board has a VLBI hardware standard interface (VSI-H) data port and keeps complete compatibility between recent VLBI data recording systems. Recently, Kimura (2005) developed a high performance software correlator, which is able to perform correlation processing of gigabit class data sets in real-time.

One of the objectives of e-VLBI is to improve the accuracy of measurements of Earth's orientation parameters (EOP), where the latency of the observations can be reduced dramatically through rapid turn-around of the data processing (Koyama et al., 2003; Koyama et al., 2004; McCool et al., 2006). In June 2004, the National Institute of Information and Communication Technology (NICT, formerly called Communications Research Laboratory) performed a one-hour e-VLBI session on the baseline between the Kashima 34-m antenna of NICT and the Westford 18-m of the Haystack Observatory, Massachusetts Institute of Technology to estimate UT1, and succeeded to obtain UT1 estimate 4.5 hours after the session was over (Koyama et al., 2005). In this experiment, the K5 software correlator combined with the network-distributed processing system named VLBI@home developed by NICT (Takeuchi et al., 2004) was used.

The development of a state-of-the-art one-channel A/D sampler "ADS3000" was successfully accomplished in order to improve the signal sensitivity of VLBI experiments (Takeuchi et al., 2006). The ADS3000 is equipped with a high performance FPGA processor, and a variety of sampling modes up to 4 Gbps are available. FPGA code is rewritable so that it can be used for multiple applications such as a digital base band converter (DBBC) for multi-channel geodetic VLBI, as a software demodulator for spacecraft downlink signal in spacecraft VLBI or satellite communications, or as a spectrometer for broadband astronomical observations.

Differential VLBI (DVLBI) technique for spacecraft navigation using e-VLBI is under development (Kikuchi et al., 2004; Sekido et al., 2004a; Sekido et al., 2004b). NICT performed six VLBI experiments for tracking HAYABUSA spacecraft on its descending phase towards asteroid Itokawa for 4 -26 November 2005 (Sekido et al., 2006). The main purpose of these observations was to evaluate the accuracy of spacecraft position determined by DVLBI. Concerning the delay observables of the spacecraft, there are two sorts of delay observables -group delay and phase delay- which are currently under investigation. The bandwidth of the spacecraft's signal is too narrow to achieve enough precision using group delay observables. Thus phase delay is thought as alternative choice to get higher delay resolution, even the ambiguity of phase is an issue to be solved (Sekido et al., 2004b; Sekido et al., 2004b). Phase delay observables are extracted with a special correlation software using the signal around transmitting frequency. In addition, a relativistic delay model for Earth-based VLBI observation of sources at finite distances was developed in order to obtain an accurate spacecraft position (Sekido and Fukushima, 2004; Sekido and Fukushima, 2006).

The presence of radio frequency interference (RFI) due to the IMT-2000 mobile phone service systems has become one of the severe problems in S-band signal observations. Thus a high-temperature superconductor (HTS) filter development for RFI mitigation was developed and is now operationally used at Kashima 34-m antenna station (Kawai et al., 2003a; Kawai et al., 2003b).

Fey et al. (2004) presented the milliarcsecond (mas)-accurate radio positions for 22 southern hemisphere extragalactic sources in order to better define the International Celestial Reference Frame and to provide additional phase-reference sources with accurate positions for use in astrophysical observations. Ojha et al. (2005) also presented the X-band VLBI survey results of southern hemisphere extra-galactic sources at milliarcsecond resolution to quantify the magnitude of the expected effect of intrinsic source structure on astrometric bandwidth synthesis VLBI observations. Niell et al. (2005) presented the new perspective of geodetic VLBI, which is called "VLBI2010".

National Astronomical Observatory of Japan (NAOJ) is operating a domestic VLBI network VERA (VLBI Exploration of Radio Astrometry). The VERA network consists of four stations and each station has a 20-m-diameter antenna. They are located at Mizusawa (Iwate Prefecture), Iriki (Kagoshima Pref.), Ogasawara (Ogasawara Islands, Tokyo) and Ishigakijima (Okinawa Pref.). The range of the baseline length in the network is 1020 km to 2270 km. The main goal of the VERA is to explore three-dimensional (3-D) structure of the Galaxy by measuring the annual parallax of Galactic maser sources with the accuracy of 10 micro arc second levels. In order to practice high-precision astrometry, VERA is required to keep the accuracy of the 3-D coordinate within 10^{-9} of the baseline length, that is 2 mm. VERA also aims at studying geophysical phenomena with high-precision positioning (Manabe et al, 2004; Tamura and VERA group, 2002).

Each VERA station is equipped with 2 GHz and 8 GHz bands (S/X bands) receivers for geodetic VLBI observations, and dual receiver system of 22 GHz and 43 GHz bands (K/Q bands) for astrometry observations. The dual receiver (dual beam) system in K/Q bands is designed for relative VLBI observations. The single beam of K band system is also used for geodetic VLBI. The backend recording system is original designed for VERA. The maximum recording rate is 1 Gbps using magnetic tape recorder. One of the VERA station Mizusawa has a disk recording system named K5 developed by NICT. Its maximum recording rate is 256 Mbps and it is used mainly domestic VLBI outside of VERA network.

The first geodetic VLBI observation within VERA network was carried out in November 2004 and regular observations started in December 2004. The regular observations are usually scheduled three times per month and each one has 24-hour observation duration. Once a month, VERA stations join the domestic JADE (JApanese Dynamic Earth observation by VLBI) experiments which are organized by GSI. Those observations are objective to linking the VERA station coordinates to the ITRF2000 (International Terrestrial Reference Frame 2000). Other observations are carried out within the VERA internal network almost twice a month. VERA network attains the observation precision of 2 mm in horizontal coordinates and 7-8 mm in vertical ones with one 24-hour observation in S/X bands (Jike et al, 2005a, 2005b; Jike et al. 2006). Since 2006, geodetic observations in K band are attempted and we get better precision than S/X bands. The daily positions of VERA stations are also monitored by continuous GPS observations. Local tie among VLBI, GPS and ground survey is discussed by Masaki et al. (2006).

Bibliography

Fey, A. L., R. Ojha, D. L. Jauncey, K. J. Johnston, J. E. Reynolds, J. E. J. Lovell, A. K. Tzioumis, J. F. H. Quick, G. D. Nicolson, S. P. Ellingsen, P. M. McCulloch, and Y. Koyama (2004): Accurate Astrometry of 22 Southern Hemisphere Radio Sources, Astron. J., **127**, 1791-1795.

Fukuzaki, Y., K. Shibuya, K. Doi, T. Ozawa, A. Nothnagel, T. Jike, S. Iwano, D. L. Jauncey, G. D. Nicolson, and P. McCulloch (2005): Results of the VLBI experiments conducted with Syowa Station, Antarctica, J. Geodesy, **79**, 379-388.

Jike, T., Y. Fukuzaki, K. Shibuya, K. Doi, S. Manabe, D. L. Jauncey, G. D. Nicolson, and P. McCulloch (2005a): First year of Antarctic VLBI observations, Polar Geosci., **18**, 26-40.

Jike, T., Y. Tamura, S. Manabe, N. Kawaguchi, K. Iwadate, O. Kameya, Y. Kan-ya, S. Kuji, H. Kobayashi, S. Sakai, K. Sato, K. Shibata, T. Hirota, T. Fujii, K. Horiai, M. Honma, T. Miyaji, T. Omodaka, and H. Imai (2005b): Start of regular geodetic VLBI observations within VERA network, Annual Rep. Nat. Astron. Observatory Japan, **7**, 48.

Jike, T., Y. Tamura, S. Manabe, and NAOJ VERA Group (2006): The First Year of VERA Geodetic Experiments, in D. Behrend and K. Baver (eds.), IVS 2006 General Meeting Proc., NASA/CP-2006-214140, USA, 56-57.

Kawai, E., J. Nakajima, H. Takeuchi, H. Kuboki, and T. Kondo (2003a): Wide-band High-temperature Superconductor Filter on 2.2GHz RFI Mitigation, IVS CRL-TDC News, **22**, 2-4.

Kawai, E., J. Nakajima, H. Takeuchi, H. Kuboki, and T. Kondo (2003b): High-temperature Superconductor Filter on 2.2GHz operating status against RFI, IVS CRL-TDC News, **23**, 10-11.

Kikuchi, F., Y. Kono, M. Yoshikawa, M. Sekido, M. Ohnishi, Y. Murata, J. Ping, Q. Liu, K. Matsumoto, K. Asari, S. Turuta, H. Hanada, and N. Kawano (2004): VLBI observation of narrow bandwidth signals from the spacecraft, Earth Planets Space, **56**, 1041-1047.

Kimura, M. (2005): Development of the software correlator for the VERA system, IVS NICT-TDC News, **26**, 26-27.

Kimura, M., J. Nakajima, H. Takeuchi, and T. Kondo (2003): 2-Gbps PC architecture and Gbps data processing in K5/PC-VSI, IVS CRL-TDC News, **23**, 12-13.

Kimura, M., J. Nakajima, H. Takeuchi, and T. Kondo (2004): High Performance PC Based Gigabit VLBI System, IVS NICT-TDC News, **25**, 64-68.

Kondo, T. (2005): Development of geodetic VLBI system and direct measurements of plate motion, J. Geod. Soc. Japan, **50**, 245-262.

Kondo, T., Y. Koyama, J. Nakajima, M. Sekido, and H. Osaki (2003): Internet VLBI system based on the PC-VSSP (IP-VLBI) board, New Technologies in VLBI, ASP Conf. Ser., **306**, 205-216.

Kondo, T., M. Kimura, Y. Koyama, and H. Osaki (2004): Current status of software correlators developed at Kashima Space Research Center, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2004 General Meeting Proc., NASA/CP-2004-212255, 186-190.

Kondo, T., Y. Koyama, H. Takeuchi, and M. Kimura (2006): Development of a new VLBI sampler unit (K5/VSSP32) equipped with a USB 2.0 interface, in D. Behrend and K. Baver (eds.), IVS 2006 General Meeting Proc., NASA/CP-2006-214140, 195-199.

Koyama, Y., T. Kondo, H. Osaki, A. E. Whitney, and K. A. Dudevoir (2003): Rapid turn around eop measurements by VLBI over the internet, in E. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 119-124.

Koyama, Y., T. Kondo, H. Osaki, M. Hirabaru, K. Takashima, K. Sorai, H. Takaba, K. Fujisawa, D. Lapsley, K. Dudevoir, and A. Whitney (2004): Geodetic VLBI Experiments with the K5 System, Third IVS General Meeting, February 9-11, 2004, Ottawa, Canada.

Koyama, Y., T. Kondo, M. Hirabaru, M. Kimura, and H. Takeuchi (2005): Research and Developments for e-VLBI Utilizing Global High Speed Network Connections, J. Nat. Inst. Info. Comm. Tech., **52**, 131-139.

Manabe, S., Y. Tamura, T. Jike, K. Horiai, and VERA Team (2004): Status and Plan of Geodetic and Astrometric Observations with VERA, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2004 General Meeting Proc., NASA/CP-2004-212255, 151-156.

Masaki, Y., S. Matsuzaka, and Y. Tamura (2006): Local tie survey at VERA Ogasawara station at site Chichijima, in D. Behrend and K. Baver (eds.), IVS 2006 General Meeting Proc., NASA/CP-2006-214140, 366.

McCool, R., R. Spencer, S. Kumar, R. Beresford, S. Durand, Y. Koyama, S. Parsley, A. Whitney, and P. Maat (2006): Enhancing the Sensitivity of Radio Telescopes Using Fiber-Optic Networks, Radio Sci. Bull., **317**, 9-18.

Niell, A., A. Whitney, W. Petrachenko, W. Schlueter, N. Vandenberg, H. Hase, Y. Koyama, C. Ma, H. Schuh, and G. Tuccari (2005): VLBI2010: A Vision for Future Geodetic VLBI, Proc. Joint Assembly of IAG, IAPSO, and IABO, August, 2005, Cairns (submitted).

Ojha, R., A. L. Fey, P. Charlot, D. L. Jauncey, K. J. Johnston, J. E. Reynolds, A. K. Tzioumis, J. F. H. Quick, G. D. Nicolson, S. P. Ellingsen, P. M. McCulloch, and Y. Koyama (2005): VLBI Observations of Southern Hemisphere ICRF Sources. II. Astrometric Suitability Based on Intrinsic Structure, Astron. J., **130**, 2529-2540.

Sekido, M. and T. Fukushima (2004): Relativistic VLBI Delay Model for Finite Distance Radio Source, in E. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 141-145.

Sekido, M. and T. Fukushima (2006): A VLBI delay model for radio sources at a finite distance, J. Geodesy, **80**, 137-149, doi:10.1007/s00190-006-0035-y.

Sekido, M., R. Ichikawa, H. Osaki, T. Kondo, Y. Koyama, M. Yoshikawa, T. Ohnishi, W. Cannon, A. Novikov, and M. Berube (2004a): Astrometry observation of spacecraft with very long baseline interferometry - a step of VLBI application for spacecraft navigation -, URSI Commission-F Triennium Open Symp. Proc., 163-170.

Sekido, M., R. Ichikawa, H. Osaki, T. Kondo, Y. Koyama, M. Yoshikawa, T. Ohnishi, W. Cannon, A. Novikov, M. Berube, and NOZOMI VLBI group (2004b): VLBI Observation for Spacecraft Navigation (NOZOMI) - Data Processing and Analysis Status Report, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2004 General Meeting Proc., NASA/CP-2004-212255, 258-262.

Sekido, M., R. Ichikawa, M. Yoshikawa, N. Mochizuki, Y. Murata, T. Kato, T. Ichikawa, H. Takeuchi, and T. Ohnishi (2006): DVLBI Test Observation at HAYABUSA's approach to ITOKAWA, Proc. 16th Workshop on Astrodynamics and Flight Mechanics (in press).

Takeuchi, H., T. Kondo, Y. Koyama, and J. Nakajima (2004): VLBI@home - VLBI Correlator by GRID Computing System, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2004 General Meeting Proc., NASA/CP-2004-212255, 200-204.

Takeuchi, T., M. Kimura, J. Nakajima, T. Kondo, Y. Koyama, R. Ichikawa, M. Sekido, and E. Kawai (2006): Development of 4-Gbps Multi-functional VLBI Data Acquisition System, Publ. Astron. Soc. Pacific (in press).

Tamura, Y. and VERA Group (2002): Geodetic Observation System in VERA, in N. R. Vandenberg and K. D. Baver (eds.), IVS 2002 General Meeting Proc., NASA/TP-2003-211619, 167-170.

3.2 SLR

Precise orbit analysis, mainly of satellite laser ranging (SLR) data, has been studied in NICT. Otsubo and Appleby (2003) quantified the optical response of spherical laser ranging satellites such as LAGEOS, AJISAI and ETALON, and revealed that the center-of-mass correction of these satellites can be dependent on the types of terrestrial SLR systems. The result of this study is listed in the website of International Laser Ranging Service (http://ilrs.gsfc.nasa.gov/). Crustal deformation is monitored in a regional SLR network around Tokyo. Significant change of site coordinates caused by the volcanic activities was detected (Schillak et al., 2006).

The spin motion of LAGEOS satellites was intensively investigated in collaboration with worldwide institutes. Otsubo et al. (2004) developed a photometry system at the Natural Environment Research Council Space Geodesy Facility at Herstmonceux, UK, to monitor the spin axis orientation and the spin rate of LAGEOS-2 satellite. Andres et al. (2004), on the other hand, explained the spin motion of the two LAGEOS satellites by developing a mathematical model called LOSSAM, at Delft University of Technology, the Netherland.

Observation performance at Shimosato Hydrographic Observatory has been improved, i.e., the single-shot precision of SLR observation has been improved: from 9.5 cm for LAGEOS-1 yearly root-mean-square (RMS) in 1986 to 1.5 cm in 2005, the total number of passes obtained at Shimosato has increased from, e.g., 541 passes of 4 satellites in 1986 to 2331 passes of 24 satellites in 2005 (Satellite Laser Ranging Group of the Japan Coast Guard, 2006). Matsushita and Sato (2005) updated terrestrial reference system and gravity model for data analysis, which improved accuracy of the estimated range biases and station position.

Japan Aerospace Exploration Agency (JAXA) developed a satellite laser ranging system with an optical telescope of 1 m in diameter. The station is located in Tanega-shima Island approximately 1000 km south-west of Tokyo. The system is able to be remotely controlled from Tsukuba Space Center of JAXA (Uchimura et al., 2004). The ranging accuracy is better than 10 mm RMS in single-shot for LAGEOS satellite.

Bibliography

Andres, J. I., R. Noomen, G. Bianco, D. Currie, and T. Otsubo (2004): Spin axis behaviour of LAGEOS satellites, J. Geophys. Res., **109**, B06403, 1-12, doi:10.1029/2003JB002692.

Matsushita, M. and M. Sato (2005): Update of terrestrial reference system and gravity model for SLR data analysis, Tech. Bull. Hydrogr. Oceanogr., **23**, 73-77. (in Japanese)

Otsubo, T. and G. M. Appleby (2003): System-dependent centre-of-mass correction for spherical geodetic satellites, J. Geophys. Res., **108**(B4), 2201, doi:10.1029/2002JB002209.

Otsubo, T., R. A. Sherwood, P. Gibbs, and R. Wood (2004): Spin motion and orientation of LAGEOS-2 from photometric observation, IEEE Trans. Geoscience and Remote Sensing, **42**, 1, 202-208.

Otsubo, T. (2005): Improving the analysis precision of satellite laser ranging data from centimeter to millimeter range, J. Geod. Soc. Japan, **51**, 1-16. (in Japanese)

Satellite Laser Ranging Group of the Japan Coast Guard (2006): Contribution to geodesy, orbit determination of artificial satellites, and establishment of the World Geodetic System as the national geodetic coordinate system of Japan by means of satellite laser ranging, J. Geod. Soc. Japan, **52**, 21-36. (in Japanese with English abstract)

Schillak, S., E. Wnuk, H. Kunimori, and T. Yoshino (2006): Crustal deformation in the key stone network detected by satellite laser ranging, J. Geod., **79**, 682-688.

Uchimura, T., M. Sawabe, S. Murata, Y. Matsuoka, T. Oldham, and J. Maloney (2004): Remote Operation of GUTS-SLR, 14th Int. Laser Ranging Workshop: Proc., 419-422.

3.3 GPS

3.3.1 GEONET

GEONET has been reinforced and revised stepwise. The first overall revision of GEONET routine analysis system was done in 2001 by utilizing the state of the art models of the GPS analysis (Hatanaka et al., 2003). After eliminating linear, annual and semiannual trends, the root mean square error of baselines of the updated system were about 3 mm for horizontal components and 1 cm for vertical component in average, and the total variance was reduced by about 50 %.

GSI (2004) summarized the recent enhancements of GEONET in 2003. They are the increase of the number of the stations to 1200 stations, introduction of a real-time capability, and the second upgrade of computing system for routine analysis. Hatanaka et al. (2005) evaluated the precision of the revised routine solutions and concluded that inconsistency of noise characteristics between different antenna types was significantly reduced by the re-designing of the network clustering. The effect of thermal deformation of antenna pillar was identified by careful analysis of time series data obtained by the near real-time solution with 6-hour sessions.

By comparing the previous height solutions with the newest ones after the revisions described in GSI (2004), Yutsudo et al. (2005) detected systematic errors in the previous solutions. They attributed the causes of those errors to modeling error of phase center variation in the previous system. They showed that the closure of land survey by GPS observation from a GEONET station to another GEONET station was improved when they used new height datum obtained by the new GEONET solutions.

GEONET Group (2004) reviewed the steps of construction of GEONET and highlighted its contributions on Earth science. Hatanaka (2006) reviewed technical developments of analysis system of GEONET along with the background history of improvements of signal/noise ratio of GPS observation in the 1990s.

3.3.2 Kinematic GPS and RTK

Hatanaka et al. (2004) briefly summarized the status of enhancement of real-time capability to GEONET done by GSI in 2003. After discussion on GSI’s motivation to start such a huge project, they also explained the technical aspects of data flow, and analysis system. Yamagiwa et al. (2006) illustrated the new GEONET with real-time capability in more detail and demonstrated successful test results of 1-Hz analysis of the 2003 Tokachi-oki earthquake with this system in post-processing mode.

Yahagi et al. (2005) tested performance of the real-time analysis system and the near real-time system with 3-hour sessions. The variance of baseline time series of 3-hours solutions is 2-3 times larger than that of the 6-hour solutions, which is a standard product of the routine analysis. Seismic waves exited by the 2004 Sumatra-Andaman earthquake was detected by post-processing kinematic analysis of the GEONET data and comparison with seismogram record showed good agreement.

Miyazaki et al. (2004) processed 1-Hz GPS data at the time of the 2003 Tokachi-oki main rupture. Comparisons of GPS displacement waveform with double integrated strong motion record show significant similarities during the shake, but the integrated seismic records suffer from artificial low frequency noise. This suggests that GPS would constrain the cumulative slip distribution better than the seismic records. Then they inverted 1-Hz GPS with multiple time window inversion. The slip distribution is in principle similar to that obtained from strong motion data, but their solution shows a better contrast to the afterslip distribution. Irwan et al. (2004) analyzed both the 1-Hz and the 30-second sampling data associated with the 2003 Tokachi-oki earthquake. They successfully obtained the seismic waveform. They also concluded that there was no recognizable precursory displacement before the arrival of seismic wave.

Ohta et al. (2006a) analyzed 1-Hz data of IGS stations associated with the 2004 Sumatra-Andaman earthquake. They succeeded in detecting large surface wave for both short (~ 10 km) and long (5000 ~ 10,000 km) baselines. The analysis was effective in discussing long period coseismic signals over the seismologically detectable frequency band. Also, the analysis demonstrated the limitation of the relative mode positioning that the analysis is no longer useful after the arrival of coseismic signal to the reference site. From this experience, importance of precise point positioning in kinematic mode (kinematic PPP) became evident. Ohta et al. (2006b) studied the error characteristics of kinematic PPP analysis by analyzing GEONET 30-second sampling data with GIPSY/OASIS-II software.

Another important application of kinematic GPS is positioning of moving object. Such technique comprises the core of marine geodesy and seafloor geodetic measurements. Terai (2003; 2004) discussed vertical positioning accuracy of survey vessels with kinematic GPS positioning technique for hydrographic surveys. Precise height determination with sub-decimeter accuracy in the sea area will be useful for the sea bottom survey. Tozawa et al. (2004) discussed vertical positioning accuracy of survey vessels with VRS-RTK (virtual reference station – realtime kinematic) technique. Kawai et al. (2005; 2006) discussed positioning accuracy of kinematic GPS for long baselines used for seafloor geodetic observations.

As an application of real-time GPS positioning, Kato et al. (2005) applied the RTK-GPS to GPS buoy to detect tsunami before its arrival to the coast and succeeded to detect the tsunami that was generated by the September 2004 earthquake that occurred offshore Kii Peninsula, central Japan.

Advances of scientific research technology over the last decade have enabled progressively better navigation positioning. The Dynamic Positioning System (DPS) is installed on the Deep Ocean Drilling Vessel “Chikyu” to keep positioning and control motions (Murata et al., 2005) and by Remote Operating Vehicle (ROV) (Yamamoto, 2005).

3.3.3 Analysis Method

Hatanaka (2003) investigated systematic difference between two different sets of coordinate solutions of GEONET, and found that there was a weak point of the network combination in the old analysis strategy of GEONET. He concluded that it magnified the inconsistency between noise characteristics of two sources of reference frame realization, which are GPS satellite orbits and a priori coordinates of fiducial sites. This finding contributed the revision of the analysis strategy resulting in improvement of the solution consistency as reported by GSI (2004). Tanaka et al. (2003) calibrated the phase characteristics of GPS antennas to improve the accuracy of the GPS positioning computation.

Koshimizu et al. (2005) found anomalous transient change in the GPS continuous observation on Asama Volcano and attributed the cause of the fluctuation to the attenuation of microwave signal from the satellite due to snow stacked on the antenna radome. They also concluded that the tilt of monument due to freeze of soil at the base causes artifacts. They showed that masking of observation data from the satellite of high elevation angles, that was affected by the stacked snow, and correction of the tilt by using data of tiltmeter of the pillar were partly effective.

Shimada (2005) analyzed GPS data observed in the Tsukuba 2000 and 2001 GPS/MET dense network campaigns, and found that the relationship between the baseline length and vertical repeatability of the baseline vector among the network sites was strong. Iwabuchi et al. (2004) investigated the characteristics of post-fit residuals computed using three types of software, and evaluated the behavior of multipath errors in the post-fit phase residuals.

3.3.4 REGMOS

GSI developed automated standalone remote GPS monitoring systems (REGMOS) for the deployment on volcanoes to monitor crustal deformations of volcanoes, where neither power supply nor cabled communication is available. GSI has been operating those systems on nine volcanoes in Japan. Machida et al. (2003) reported the recent experiences gained through field operations. They described problems encountered, and some countermeasures developed to solve those problems. In 2004, GSI deployed REGMOS to Asama volcano, which erupted in September 2004. Numakawa et al. (2005) described technical details of the instrumentation.

Bibliography

Geographical Survey Institute (2004): Establishment of the nationwide observation system of 1,200 GPS-based control stations, J. Geogr. Surv. Inst., **103**, 1-51. (in Japanese)

GEONET Group (2004): GEONET (GPS Earth Observation Network System) and its Prospect, J. Geod. Soc. Japan, **50**, 53-65. (in Japanese with English abstract)

Hatanaka, Y. (2003): Remarks on Network Cluster Topology for Distributed Analyses of Wide Area GPS Networks, Technical Report, J. Geod. Soc. Japan, **49**, 143-152.

Hatanaka, Y. (2006): Enhancement of Continuous GPS Observation Networks as Geoscientific Sensors, - Resolving Signal/Noise of GPS Observable-, J. Geod. Soc. Japan, **52**, 1-19. (in Japanese with English abstract)

Hatanaka, Y., T. Iizuka, M. Sawada, A. Yamagiwa, Y. Kikuta, J. M. Johnson, and C. Rocken (2003): Improvement of the Analysis Strategy of GEONET, Bull. Geogr. Surv. Inst., **49**, 11-34.

Hatanaka, Y., A. Yamagiwa, M. Iwata, and S. Otaki (2004): Addition of real-time capability to the Japanese dense GPS Network, Proc. IGS workshop.

Hatanaka, Y., A. Yamagiwa, T. Yutsudo, and B. Miyahara (2005): Evaluation of Precision of Routine Solutions of GEONET, J. Geogr. Surv. Inst., **108**, 49-56. (in Japanese)

Irwan, M., F. Kimata, K. Hirahara, T. Sagiya, and A. Yamagiwa (2004): Measuring Ground Deformation with 1-Hz GPS Data: the 2003 Tokachi-oki Earthquake (Preliminary Report), Earth Planets Space, **56**, 389-393.

Iwabuchi, T., Y. Shoji, S. Shimada, and H. Nakamura (2004): Tsukuba GPS Dense Net Campaign observation : Improvement in GPS stacking maps of post-fit phase residuals estimated from three software packages, J. Meteor. Soc. Japan, **82**, 315-330.

Kato, T., Y. Terada, K. Ito, R. Hattori, T. Abe, T. Miyake, S. Koshimura, and T. Nagai (2005): Tsunami due to the 2004 September 5th off the Kii peninsula earthquake, Japan, recorded by a new GPS buoy, Earth Planets Space, **57**, 297-301.

Kawai, K., Y. Narita, M. Fujita, T. Ishikawa, H. Fuchinoue, and M. Nagaoka (2005): Machine (antenna) - dependency of long baseline KGPS positioning accuracy, Tech. Bull. Hydrogr. Oceanogr., **23**, 66-72. (in Japanese)

Kawai K., M. Fujita, T. Ishikawa, Y. Matsumoto, and M. Mochizuki (2006): Accuracy evaluation of the long baseline KGPS, Tech. Bull. Hydrogr. Oceanogr., **24**, 80-88. (in Japanese)

Koshimizu, H., N. Ishikura, T. Amagai, M. Nemoto, K. Iwata, A. Yamada, K. Numakawa, and H. Shimo (2005): Investigation and Countermeasure against the obstacle to measurement at mobile observation, J. Geogr. Surv. Inst., **109**, 55-63. (in Japanese)

Machida, M., Y. Ebina, H. Shinno, and T. Akiyama (2003): Some aspects and its improvement of remote GPS monitoring system for volcanic activities, J. Geogr. Surv. Inst., **102**, 71-80. (in Japanese)

Miyazaki, S., K. M. Larson, K. Choi, K. Hikima, K. Koketsu, P. Bodin, J. Haase, G. Emore, and A. Yamagiwa (2004): Modeling the rupture process of the 2003 September 25 Tokachi-Oki (Hokkaido) earthquake using 1-Hz GPS data, Geophys. Res. Lett. , **31**, L21603, doi:10.1029/2004GL021457.

Murata, K., H. Ozawa, T. Tsubokawa, M. Yoshitake, and J. Takeshina (2005): Dynamic Positioning System for Deep Ocean Drill Ship CHIKYU", 7th Int. Symp. on Mar. Engineering (ISME TOKYO 2005).

Numakawa, K., H. Shimo, K. Nemoto, T. Akiyama, H. Shinno, K. Iwata and A.Yamada (2005): Remote GPS monitoring system at Asama Volcano, J. Geogr. Surv. Inst., **107**, 5-8. (in Japanese)

Ohta, Y., M. Irwan, T. Sagiya, F. Kimata, and K. Hirahara (2006a): Large surface wave of the 2004

Sumatra-Andaman earthquake captured by the very long baseline kinematic analysis of 1-Hz GPS data, Earth Planets Space, **58**, 153-157.

Ohta, Y., T. Sagiya, and F. Kimata (2006b): Assessment of the long-term stability of the PPP kinematic GPS, J. Geod. Soc. Japan, **52**, 309-318. (in Japanese with English abstract)

Shimada, S. (2005): Vertical repeatability of the GPS measurements in the Tsukuba GPS/MET dense-network campaigns, in E. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 21-25.

Tanaka, Y., A. Kagawa, T. Kawahara, and H. Tsuji (2003): GPS Antenna Calibration and Its Issues, J. Geogr. Surv. Inst., **102**, 63-69. (in Japanese)

Terai, K. (2003): The accuracy estimation of vertical kinematic GPS positioning on shipboard and an attempt to grasp of top and bottom exercise of ship by kinematic GPS observation, Tech. Bull. Hydrogr. Oceanogr., **21**, 51-61. (in Japanese)

Terai, K. (2004): Precise vertical position fixing by kinematic GPS, Hydro International, 8(10), 7-9.

Tozawa, M., Y. Matsumoto, T. Yabuki, T. Chujo, Y. Amemiya, and T. Ueki (2004): Evaluation of vertical positioning accuracy by VRS-RTK system on S/V, Tech. Bull. Hydrogr. Oceanogr., **22**, 13-19. (in Japanese)

Yahagi, T., T. Yutsudo, H. Kojima, and Y. Hatanaka (2005): Status of Emergency Analysis of GEONET, J. Geogr. Surv. Inst., **108**, 29-37. (in Japanese)

Yamagiwa, A., Y. Hatanaka, T. Yutsudo, and B. Miyahara (2006): Real-time capability of GEONET system and its application to crust monitoring, Bull. Geogr. Surv. Inst., **53**, 27-33.

Yamamoto, I. (2005): Deep sea crusing underwater vehicle construction technology, Bull. Naval Architects Japan, **5**, 885, 107-110. (in Japanese)

Yutsudo, T., M. Iwata, T. Amagai, H. Kojima, T. Yahagi, B. Miyahara, and Y. Hatanaka (2005): Altitudes of GPS-based Control Stations, J. Geogr. Surv. Inst., **106**, 21-30. (in Japanese)

3.4 SAR

SAR Interferometry (InSAR) has become a popular tool to monitor crustal deformation due to tectonic, volcanic, and hydrological processes. In vegetated regions like Japan, however, SAR satellite with C-Band sensors were not quite useful. There had been no L-Band satellites since operation of JERS-1 has stopped in 1998. JAXA has successfully launched ALOS on 24 January 2006, and the routine operation has started in October 2006. ALOS is equipped with three remote sensing instruments including a Phased Array type L-band SAR (PALSAR). PALSAR is quite useful in monitoring vegetated area like Japan, and is used to investigate crustal movements all over the world on a routine bases. Image data taken by ALOS can be utilized to international scientific community on the proposal basis. For more information, please visit the Earth Observation Research Center (EORC) of JAXA at http://www.eorc.jaxa.jp/ALOS/.

Tobita (2003) developed software for InSAR. The software has been contributing to mapping of crustal deformations associated with earthquakes and volcanism. Using interferometric data obtained with his software, he studied coherence of JERS-1 SAR interferograms and showed that L-band InSAR was preferable over vegetated and mountainous regions like most of Japan. He gave an empirical equation to relate the attainable coherence and the orbital distance. This equation is useful to select pairs of reasonable coherence before processing. Tobita et al. (2005) developed an algorithm for integration of InSAR and GPS. The vertical displacements derived from a combination of JERS-1 InSAR and GEONET GPS agreed well with the leveling survey in areas of ground subsidence due to ground water pumping in Kanto Plain, Japan.

Omura promoted two domestic workshops on InSAR, supported by the Earthquake Research Institute, University of Tokyo (ERI), Cooperative Research Program on September 2004 (Omura, 2005) and October 2006.

Bibliography

Omura, M. ed. (2005): Proc. 2004 ERI Workshop on Evolution of Interferometric SAR (Workshop: 2004-W-09), September 29-30, 2004, Earthq. Res. Inst., Univ. Tokyo. (in Japanese) http://www.eri.u-tokyo.ac.jp/KOHO/KYODORIYO/report/2004-W-09/index.html

Tobita, M. (2003): Development of SAR Interferometry Analysis and its Application to Crustal Deformation Study, J. Geod. Soc. Japan, **49**, 1-23. (in Japanese with English abstract)

Tobita, M., H. Munekane, S. Matsuzaka, M. Kato, H. Yarai, Mak. Murakami, S. Fujiwara, H. Nakagawa, and T. Ozawa (2005): Studies on InSAR data processing technique, J. Geogr. Surv. Inst., **106**, 37-49. (in Japanese)

3.5 Other Techniques

3.5.1 Leveling

Ohtaki (2003) developed an improved method to correct a refraction error of precise leveling. The first step of his method is to calculate a refraction error for individual reading using the data, such as distance between the spirit level and staff, height difference, and atmospheric temperature, and to sum up each error of individual reading. He concluded that this method gave better closure residual than existing methods.

3.5.2 APS

GSI has been using APS (Automated EDM Measurement Unit) for continuous crustal deformation monitoring. Shinno et al. (2003) described the technical improvements applied for the control mechanism and electric circuits for power supply and data telemetry of the instrument, which has been operating on Iwate Volcano since 1998. They also reported the technical detail of APS unit that was deployed and installed to monitor the deformation of the caldera of Izu-Oshima Volcano since 2002.

3.5.3 Orbit Determination of Satellites

The orbit determination study was extended to low Earth orbit satellites. The twin satellites of Gravity Recovery And Climate Experiment (GRACE), for instance, are monitored by GPS, SLR and K-band inter-satellite range. Gotoh et al. (2006) applied various orbit determination methods to the GRACE data, and confirmed cm-order agreements.

3.5.4 Remote Monitoring of Gravity

Ikeda et al. (2005) constructed a system to monitor the state of a superconducting gravimeter (SG) at Syowa Station remotely from Japan via satellite communication.

3.5.5 Technology Development for a Future Satellite Gravity Mission

The current accuracy of satellite-to-satellite ranging measurements is limited by the wavelength of microwave used. To improve the performance of ranging measurements, a development was considered for satellite-to-satellite laser interferometer technique. As a feasibility study of future satellite gravity mission, a ground simulator was developed at NICT in cooperation with NAOJ and Niigata University (Nagano et al., 2004; 2005), and demonstrated that the system reached nearly the required noise level.

Bibliography

Gotoh, T., T. Otsubo, and T. Kubo-oka (2006): GPS based precise orbit determination of low earth orbiters evaluated with SLR and K-band range observations, IEICE Trans. on Communications, **J89-B**, 7, 1151-1157. (in Japanese)

Ikeda, H., K. Doi, Y. Matushima, F. Kishida, K. Iimura, and K. Shibuya (2005): Monitoring system for the superconducting gravimeter at the Syowa Station, Antarctica, J. Cryo. Soc. Japan, **40**(9), 368-371. (in Japanese with English abstract)

Nagano, S., T. Yoshino, H. Kunimori, M. Hosokawa, S. Kawamura, T. Sato, and M. Ohkawa (2004): Displacement measuring technique for satellite-to-satellite laser interferometer to determine Earth's gravity field, Meas. Sci. Technol. **15**, 2406-2411.

Nagano, S., M. Hosokawa, H. Kunimori, T. Yoshino, S. Kawamura, M. Ohkawa, and T. Sato (2005): Development of a simulator of a satellite-to-satellite interferometer for determination of the Earth's gravity field, Rev. Scientific Instruments, **76**, 124501.

Ohtaki, M. (2003): Influence of Errors by Refraction on Precise Leveling, J. Geogr. Surv. Inst., **101**, 9-21. (in Japanese)

Shinno, H., A. Yamada, K. Morita, S. Okamura, and Y. Takabatake (2003): Improvement of APS Continuous Observation Unit, J. Geogr. Surv. Inst., **102**, 81-90. (in Japanese)

4. General Theory and Methodology

Various studies have been done to develop special methodology to study crustal deformation and stress associate with tectonic and seismic deformation. Iinuma et al. (2005) applied Hori's method for stress inversion without knowledge of full constitutive relation between strain and stress and estimated stress field of the Japanese Islands based on GPS velocity field derived from GEONET. Fukuda et al. (2004) introduced Monte Carlo Mixture Kalman Filter to the geodetic inversion analysis to derive more accurate estimates for the transient phenomena compared with conventional approach using the Kalman filter. Okada (2003) carried out a theoretical consideration about the character of vertical displacement due to a fault model. Kobayashi (2005) propose a spatial monitoring procedure of GPS data using smoothing method.

Although there are many previous works to estimate crustal deformations around a subduction zone during one or over many repeated seismic cycles, they are not free from unrealistic assumptions to avoid intrinsic numerical difficulties; some ignore the Earth's self-gravitation, some compressibility, and others radial stratification. Okubo et al. (2003) and Okuno et al. (2004) developed a new recipe to compute postseismic deformation in a realistic, spherically symmetric, non-rotating, visco-elastic, and isotropic (SNRVEI) Earth. The calculation is done without the above-mentioned unrealistic approximations. The essential point of the new algorithm is to perform Laplace inversion integration without evaluating contribution from the innumerable poles. Using this method, they presented a complete set of the Green function, i.e. time variations of displacement, gravity, geoid height on the surface for four independent types of point dislocation: strike-slip on a vertical plane, dip-slip on a vertical plane, tensile faulting on a horizontal plane and tensile faulting on a vertical plane. As an Earth model, they employ the 1066A Earth model together with the standard viscosity profiles. The result shows a diverse spatial pattern due to a viscous structure or a source depth. In particular, ratio of the source depth to the lithosphere thickness governs the evolution of the postseismic deformation. Of particular interest is that the far-field deformation (epicentral distance > a few hundreds of km) clearly reveals transient behavior. This makes a contrast to the near field deformation where coseismic change dominates. It follows that postseismic gravity change might be detected with satellite missions because the wavelength exceeds 100 km, if a sufficiently large earthquake occurs. If the back-slip hypothesis holds at a subduction zone, integration of the Green functions over a finite fault plane allows us to compute both transient and secular displacement and gravity change. They compared the theoretical result with the observed secular uplift and gravity change at Tokai Region where a large earthquake is anticipated to occur in a near future.

Sun (2004) presented an asymptotic solution of static displacements excited by a point dislocation in a spherical symmetric Earth model as an approximation of the dislocation theory for a spherical Earth model (Sun et al., 1996). The solution is mathematically simple and physically reasonable since it reflects Earth's sphericity and radial structure. Comparison of the asymptotic results with both the exact results and the corresponding flat-Earth results shows that for any distances the exact results are approximated better by the asymptotic results than by the flat-Earth results. For a homogeneous sphere, both theoretical and numerical investigations indicate that the solution is valid for all types of seismic sources and for an epicentral distance of at least 20° with a relative error less than 1 % compared to results calculated for a spherical Earth model (Sun et al., 1996). For a vertical strike-slip source, the asymptotic solution is valid for the entire Earth surface. For the 1066A Earth model, it is found that the asymptotic solutions are sensitive to the vertical derivatives of model parameters. The sensitivity can be used to study the vertical structure of the Earth. It is also found that the sphericity effect can be well reflected in the asymptotic solution, and can reach 20 % discrepancy in the near field for a deep source. Owing to its mathematical simplicity, this solution can be applied easily to calculate coseismic displacement, just as the theory for a half space Earth model like Okada (1985).

Sun et al. (2006) presented a set of Green's functions for calculating the coseismic strain caused by four independent seismic sources in a spherically symmetric, non-rotating, perfectly elastic, and isotropic (SNREI) Earth model. Corresponding expressions are derived assuming that the seismic sources are located at the polar axis. The proper combination of these expressions allows calculation of the coseismic strain components resulting from an arbitrary seismic source at any position on the Earth. Calculations of strain components in the near field agree well with those calculated for a half-space Earth model, thus confirming the validity of their theory. Furthermore, they investigated effects of spherical curvature and the stratified structure of the Earth on coseismic strain changes. Curvature effects are small for three types of seismic sources, but extremely large for the horizontal tensile opening on the vertical fault plane. Because a general coseismic deformation comprises four independent solutions, the large curvature effect on the horizontal tensile opening source contributes to the general result. Effects of Earth's stratified structure are large for all depths and epicentral distances. They reach a discrepancy greater than 30% almost everywhere, and 100 % in a very far field. Results show that effects of crustal structure mainly exist in the near field; they do not affect results for a far field.

Fu and Sun (2004) presented a segment-summation scheme for calculating coseismic deformations caused by a seismic model with spatial distribution of fault slip. The basic idea is to divide such a fault plane into limited sub-faults, so that the coseismic deformations caused by each sub-fault can be evaluated by applying Okada's formulation (Okada, 1985) and summing up the individual contributions from the whole sub-faults. Two case studies of the 1999 Chi-Chi earthquake (Mw7.6) and the 2001 Kunlun earthquake (Mw7.8) show that there exists a big discrepancy between the results calculated for the two dislocation models. It implies that the mean dislocation model remarkably affect the calculating results. The results of RMS errors show that the coseismic displacements calculated by the fault with spatial distribution of fault slip improve the results by over 50 % compared to the mean dislocation results.

Fu and Sun (2006) presented and discussed the global coseismic displacements caused by the 2004 Sumatra-Andaman earthquake, using quasi-static dislocation theory for a spherically symmetric Earth model (Sun et al., 1996). Theoretical calculations are performed with a heterogeneous slip distribution fault model based on Ammon et al. (2005). Results show that the coseismic horizontal displacements are large to the north-east and south-west of the fault plane. Even as far as 6000 km from the epicenter, more than 1 mm coseismic horizontal displacements raised from the earthquake. Their work has three contributions: to validate the fault model (Ammon et al., 2005) by geodetic data; to interpret the displacements observed by GPS; and to provide a reference for other researchers or for other geodetic applications. Overall, the modelled and observed displacements basically agree with each other in both the near field and far field. The calculated displacements are generally smaller than the observed ones, since considerable moment is released by slow-slips and/or aftershocks which has not been included in the fault model.

Nakamura and Takenaka (2004) developed software, which searches fault parameters on the plate interface by using observed strain data.

Bibliography

Fu, G. and W. Sun (2004): Effects of spatial distribution of fault slip on calculating co-seismic displacements – case studies of the Chi-Chi earthquake (m=7.6) and the Kunlun earthquake (m=7.8), Geophys. Res. Lett., **31**, L21601, doi:10.1029/2004GL020841.

Fu, G. and W. Sun (2006): Global co-seismic displacements caused by the 2004 Sumatra-Andaman Earthquake, Earth Planets Space, **58**, 149-152.

Fukuda, J., T. Higuchi, S. Miyazaki, and T. Kato (2004): A new approach to time-dependent inversion of geodetic data using a Monte Carlo mixture Kalman filter, Geophys. J. Int., **159**, 17-39, doi: 10.1111/j.1365-246X.2004.02383.x.

Iinuma, T., T. Kato, and M. Hori (2005): Inversion of GPS velocity and seismicity data to yield changes in stress in the Japanese Islands, Geophys. J. Int., **160**, 417-434.

Kobayashi, A. (2005): Spatial monitoring of GPS coordinates using 3-hour analysis in the Tokai area, Quarterly J. Seism., **68**, 99-104. (in Japanese)

Nakamura, K. and J. Takenaka (2004): The support software for estimation of interplate slip, Quarterly J. Seism., **68**, 25-35. (in Japanese)

Okada, Y. (2003): Paradox on vertical displacement due to a fault model, J. Geod. Soc. Japan, **49**, 99-119.

Okubo, S., J. Okuno, and Y. Tanaka (2003): Viscoelastic deformations during a seismic cycle and over cycles around a subduction zone, **-** simulation for a realistic SNRVEI Earth **-**, IUGG, Sapporo.

Okuno, J., S. Okubo, and Y. Tanaka (2004): Secular changes of displacement and gravity around subduction and collision zones, **-** Simulation for a realistic SNRVEI earth **-**, European Geosciences Union General Assembly, 2004.

Sun, W. (2004): Asymptotic solution of static displacements caused by dislocations in a spherically symmetric Earth, J. Geophys. Res., **109**, B05402, doi:10.1029/2003JB002793.

Sun, W., S. Okubo, and G. Fu (2006): Green's functions of coseismic strain changes and investigation of effects of Earth's spherical curvature and radial heterogeneity, Geophys. J. Int., **167**, 1273-1291.

5. Determination of the Gravity Field

5.1 International and Domestic Gravimetric Connections

GSI has been responsible for national gravity connection surveys in Japan by using LaCoste and Romberg (LCR) gravimeters model-G together with absolute gravity meters. The third nationwide survey, started in April 2001, has basically been completed, except for Hokkaido Island, which included relative gravity measurements at 18 Fundamental Gravity Stations (FGSs), 64 first-order gravity stations and 17 benchmarks between April 2002 and December 2006.

GSI has also conducted an international gravity connection survey in East and South-East Asia by relative gravity measurements in conjunction of the establishment of the Absolute Gravity Standard Station Network in East Asia and South-East Asia, which will be described in more detail in Section 5.2. The resulting gravity values in the region show a tendency that they are larger than those reported in the International Gravity Standardization Net 1971. Nevertheless, they agree within about 100 micro-gal.

GSJ/AIST conducted a gravity survey at Vulcano and Lipari Volcanoes, Eolia Islands, southern Italy, in 2004. The total number of measurement points amounted to about 510, and stations were arranged at a very short interval of about 200 m to 1 km. The surface density of Vulcano Volcano was estimated to be about 1.8 x 10^3 kg/m^3, which is very small compared to those of other volcanoes.

The Disaster Prevention Research Institute, Kyoto University (DPRI) and GSJ/AIST, in cooperation with Seismological Bureau of Yunnan Province, conducted a series of gravity survey in Lijiang Basin, Yunnan Province, China, in 2003 and 2004, respectively. The total number of measurement points amounted to about 700. A 3-D bedrock-model was obtained from gravity analysis, so the underground structure, i.e. thickness of the sedimentary layer or the location of an active fault which caused the 1996 Lijiang earthquake, was defined.

5.2 Absolute Gravimetry

GSI carried out absolute gravity measurements at 18 FGSs with three FG5 absolute gravimeters (Micro-g LaCoste Inc.: No.104, No.201 and No. 203). Four of these 18 stations were newly established, namely, Hakodate, Iida, Sendai, and Okayama FGSs. The existing FGSs are: Obihiro, Hirosaki, Esashi, Matsushiro, Nagaoka, Tsukuba, Kanozan, Mt. Fuji, Omaezaki, Kanazawa, Kyoto-C, Matsue, Hiroshima, and Naha FGSs.

Kyoto University and GSI have collaborated to establish the Absolute Gravity Standard Station Network in East Asia and South-East Asia as a part of the Asia-Pacific Space Geodynamics Project cooperation campaigns in IAG and PCGIAP, using FG5 absolute gravimeters. From 2002 to 2005, they measured absolute gravity values in the accuracy of micro-gal in Wuhan, Nanning, Shanghai, Beijing, Kunming, Lhasa, Hong-Kong, Wulumuqi, Xi'an and Xining in China, Hsinchu in Taiwan, Bandung, Yogyakarta, Cibinong and Pontianak in Indonesia, Kuala Lumpur and Kota Kinabalu in Malaysia, Bangkok and Cheng-Mai in Thailand, and Manila in the Philippines as well as Kyoto, Esashi, Matsushiro, Kamioka, Muroto, Aso, Mizunami, and Naha in Japan. As an extension of these campaigns in the southern hemisphere, they have conducted absolute gravity measurements in Perth and Canberra in Australia, and at Syowa Station in Antarctica in 2003-2004 (Higashi et al., 2002; Higashi et al., 2003; Fukuda et al., 2004; Kimura et al., 2004; Takemoto and Sun, 2004: Fukuda et al., 2005a; Hiraoka et al., 2006; Takemoto et al., 2006a; Takemoto et al., 2006b).

GSJ/AIST carried out the so-called hybrid gravity measurements at Ogiri Geothermal Field in March and April 2003, and detected small changes in gravity less than five micro-gal. Field wide shut-in of production/reinjection wells of the geothermal power plant took place during the measurements, and the distribution of the stations with gravity increase and decrease during shut-in is consistent with the locations of main production and re-injection zones, respectively. It can be reproduced by numerical simulation based on a reservoir model constructed from various reservoir engineering data.

5.3 Gravimetry in Antarctica

GSI and Kyoto University conducted absolute gravity measurements with both FG5 No. 203 and No. 210 at the International Absolute Gravity Basestation Network (IAGBN) A 0417 and its backup site at Syowa Station, Antarctica, from December 24, 2003 to January 31, 2004 as an activity of the 45th Japanese Antarctica Research Expedition (JARE) (Fukuda et al. 2005a; Hiraoka et al., 2005). Nearly continuous observation was carried out for one month. The gravity values obtained by both FG5s agree within 1 to 3 micro-gal at these two sites.

The temporal gravity changes obtained in comparison with the previous absolute gravity measurements collected with FG5 in 1994/1995 and in 2000/2001 show a gravity trend of - 0.27 micro-gal/yr, which agrees with the tendency of ground uplift. However, the error of the estimated rate of gravity decrease is quite large, when compared to the prediction of a crustal deformation model associated with post glacial rebound or the estimated rate of vertical changes obtained from VLBI and GPS observation.

Iwano et al. (2003) and Fukuda et al. (2005b) carried out observations at Syowa Station with a SG and an absolute gravimeter FG5 in parallel for the purpose of calibration of the SGs, and determined the scale factor for TT70 No. 016 and CT No. 043, respectively.

Kobayashi et al. (2004) made a detailed coastline data set along Lutzow-holm Bay, Antarctica, and calculated oceanic tidal effects on gravity, radial and horizontal displacements at Syowa Station and in nearby areas.

Iwano and Fukuda (2004) reported the possibility of using SG observations without a tilt compensation system. Iwano et al. (2005) determined long period gravimetric tidal parameters from 10 years of SG observations at Syowa Station. They showed that the combination of an inelastic Earth model with Schwiderski’s ocean model gave the best agreement with the observations.

In April 2003, a new SG CT No. 043 was installed at Syowa Station as a successor to TT-70 No. 016 (Ikeda et al., 2004; 2005). The gravity changes associated with the 2004 Sumatra-Andaman earthquake were recorded by the gravimeter CT No. 043, and the tsunami induced by the earthquake was also observed by tide gauge at Syowa Station. Nawa et al. (2006a; 2006b) and Nawa (2006) investigated influences of the tsunami on gravity changes associated with the earthquake.

For detecting ice sheet mass movements, Fukuda et al. (2003) proposed an effective configuration of in-situ precise gravity measurements in combination with GPS measurements on ice sheet, and conducted several experiments of the precise gravity measurements on ice sheet near Syowa Station during JARE-45. They concluded that the measurements with an appropriate data processing can reach a 10-micro-gal-accuracy even on the moving ice sheet.

5.4 Tidal Gravity Changes and Loading Effects

ERI and GSI have continued absolute gravity measurement several times a year since 1996 at Omaezaki FGS; in this area, the Tokai earthquake is anticipated to occur in a near future. GSI made continuous absolute gravity measurements with FG5 No. 104 from September 2002 to April 2003 and re-occupied the station with FG5 No. 203 or No. 201 three times afterwards. The gravity values there appear to remain unchanged, although the ground is subsiding at a rate of 5-10 mm/yr during the last 10 years.

In order to detect the gravity changes associated with the 2003 Tokachi-oki earthquake, GSI made absolute gravity measurements with FG5 No. 201 at Obihiro FGS in March 2004 (Tsuji et al., 2004). The results reveal a gravity increase of about 20 micro-gal in comparison with the 1998 measurement, correspond to a subsidence of 7 cm, and are in good accordance with those obtained by leveling and tidal observations between 1997 and 2003.

When the number of low-frequency earthquakes increased in Mt. Fuji area in October 2000, GSI made absolute gravity measurements with FG5 No. 203 at Mt. Fuji FGS and relative measurements with LCR model-G gravimeters at Mt. Fuji FGS and surrounding 21 benchmarks repeatedly in May-July 2001, June 2002, and July 2003 (Hiyama et al., 2003), respectively. The results reveal that at Mt. Fuji FGS the gravity increased by about 9 micro-gal between 2001 and 2002 and by about 4 micro-gal between 2002 and 2003. The gravity measurements do not show any common trend of increase/decrease in the surrounding area between 2001 and 2002. However, a trend of increase of gravity was indeed measured at most of the sites in the area between 2002 and 2003.

5.5 Non-tidal Gravity Changes

5.5.1 Gravity Changes Associated with Crustal Deformation and Seismic and Volcanic Activity

JHOD carried out gravity surveys at volcanic islands of the Izu-Ogasawara arc in 2002 in order to detect a vertical crustal movement (Hydrographic and Oceanographic Department, 2003).

Repeated gravity measurements at Iwo-jima caldera detected a gravity change of 0.23 mgal in association with the uplift of about 1 m from 2000 to 2002, suggesting the significant contribution of magma intrusion (Ukawa et al., 2006).

ERI repeated absolute gravity measurements at selected sites along the coast of the Japan Islands. The target of the campaign is to detect gravity changes around the subduction zones (Kurile and Japan Trenches, and Tonankai and Nankai Troughs).

GGP Japan and ERI have detected changes in gravity acceleration associated with the 2003 Tokachi-oki earthquake of M8.0 using high-resolution continuous gravity recordings from a local network of SGs (Imanishi et al., 2004). Detected changes in gravity acceleration are smaller than 1 micro-gal and agree well with theoretical values calculated from the dislocation model. This proves that precise gravimetry with a network of superconducting gravimeters can contribute significantly to the study of earthquake source processes.

ERI, Hokkaido University and GSI detected a much larger (>10 micro-gal) gravity change due to the same earthquake around the source area (Okubo et al., 2005a). They inverted the gravity changes and the displacements from GPS to construct a fault model.

Okubo (2005) summarized recent development of gravity observation and theoretical works on gravity changes that enable us to infer mass transport during volcanism with reasonable accuracy. Combination of both absolute and relative gravity measurement, namely hybrid gravity measurement, provides us with “absolute” gravity data on local to regional scales. The data, together with crustal movement, can be inverted for physical models of volcanism. The strategy gives us invaluable information on how underground masses were transported during the event of Miyake-jima eruption in 2000 and that of Mt. Asama in 2004.

Many low-frequency earthquakes were observed under Mt. Fuji in 2000 and 2001. Shizuoka University carried out precise relative gravity measurements over Mt. Fuji to monitor temporal gravity changes associated with its volcanic activity between 2002 and 2004, jointly with ERI, Tokai University and Tohoku University (Satomura et al., 2005). The number of the low-frequency earthquakes decreased after 2001 and no significant gravity changes were observed.

Eruptive and caldera-forming activity at Miyake-jima Island, Japan, commencing on 26 June 2000, was accompanied by more than 40 days of seismic swarms and significant crustal deformation in the nearby islands and sea region besides those at Miyake-jima itself. The migration of the hypocenters at the early stage suggests that they were triggered by magma intrusion from Miyake-jima. However, it remains uncertain whether the long-lasting seismic swarms and ground displacements in the northern Izu Islands were totally maintained by the magma flow from Miyake-jima, because another magma source near Kozu-shima, located at 40 km northwest of Miyake-jima, was suggested previously on the basis of anomalous ground displacements. ERI and Nagoya University reported the detection of changes in both absolute gravity and elevation associated with the 2000 activity at Kozu-shima and Miyake-jima. Combining these data with horizontal GPS displacements, they extended the analysis of Nishimura et al. (2001) and constructed an optimum source model, so that they could account for the observed changes in geodetic data and determined the mass budget of the magma flow. The total mass of the newly intruded dike offshore of Miyake-jima and nearby Kozu-shima turned out to be 130 % or greater than the lost mass at Miyake-jima. As long as there are no other source elements, another magma reservoir near Kozu-shima is required and is suggested to have been activated, causing the seismic swarms and crustal deformation. We may speculate as a phenomenology that the rapid lateral magma flow from Miyake-jima in the very beginning of the unrest awakened a dormant reservoir offshore of Miyake-jima and Kozu-shima.

The 2000 eruption of Miyake-jima Volcano surprised the world with the rapid caldera formation (1600 m in diameter and 400 m in depth) in two months without ejecting the corresponding mass to the surface. ERI and Hokkaido University reported the spatio-temporal gravity changes before and after caldera collapse at Miyake-jima Volcano in 2000 (Furuya et al., 2003b). A gravity decrease of as much as 145 micro-gal at the summit area since June 1998 had been detected 2 days before the collapse, interpreted as reflecting the formation of a large void beneath the volcano. Gravity changes detected after the initiation of collapse can mostly be corrected by the effect of collapsed topography, from which a rapid rate of collapse at more than 1.6 x 10^7 m^3/day can be inferred. Correcting for the effect of topographical change, they identified a temporal decrease in gravity from the middle of July to the late August despite ground subsidence. The gravity decrease is interpreted as a reduction of the density in a cylindrical conduit, attributed to water inflow from an ambient aquifer that also promoted intensive magma-water interaction and subsequent explosive eruptions. From September to, at least, November 2000, gravity values at all the sites increased significantly to a degree that cannot be explained by ground displacement alone. They attributed this temporal evolution primarily to magma ascent and refilling of the conduit.

Asama Volcano, one of the most active andesitic volcanoes in Central Japan, started a series of eruptions on 1 September 2004, and the eruptive activity lasted about three months. Tohoku University, ERI, and Hokkaido University have carried out microgravity measurements at the volcano three times; one year before, immediately after the eruption and one and a half months later (Ueki et al., 2005). They combined relative measurements over the area with an absolute measurement at a reference station to observe temporal changes in absolute gravity value. The data obtained before and after the eruption show that the gravity changes preceding the eruption are from - 6 to + 9 micro-gal, which are of about the same as the accuracy of observations. The gravity changes predicted from the tensile fault models and Mogi models proposed that the ground deformations are always less than 1 micro-gal at any gravity station. The observational fact that gravity changes did not exceed 10 micro-gal provides some constraints on the magma accumulation in the conduit. A numerical examination suggests that the volume of the magma accumulated in one year preceding the eruption may be less than 2 x 10^7 m^3.

DPRI and ERI began absolute gravity measurements with a FG5 and relative gravity measurements with LCR gavimeters in 1998 at Sakura-jima Volcano, South Kyushu, Japan, in order to clarify both spatial and temporal changes of gravity accurately in the absolute sense. Yamamoto et al. (2003) summarized and evaluated the observed gravity changes during the period from 1998 to 2002. They found that the observed gravity increase in the central region of the volcano during the period of active stage with continuous summit eruptions since 1975 stopped during almost all their observation periods. The phenomenon seems to be related to the decreased activities of summit eruptions in recent years.

DPRI has been carried out gravity measurements in Tokai District, Central Japan, in Kii Peninsula, West Japan, and in Muroto Peninsula, South-Eastern part of Sikoku Island, West Japan every year for more than 30 years by using LCR gavimeters. The gravity in the inland part of Tokai District shows a gradual increase at a rate of 3 micro-gal/yr with respect to that in the coastal area, which correlates well with that of the ground subsidence in Tokai District. It is revealed that the spatial pattern of the gravity change rates inflects at about 30 km inland from the coast line of Omaezaki Cape. In Kii Peninsula or in Muroto Peninsula, however, no clear gravity increase was observed, which might be caused by the crustal deformation associated with the preparatory processes of the anticipated Tonankai or Nankai earthquake.

5.5.2 Gravity Changes Associated with Groundwater Level

Tanaka et al. (2006) performed repeated absolute gravity measurements at the Mizunami Underground Research Institute construction site where continuous pore water pressures had been monitoring at different depths. They found that the gravity variations were caused mostly by both coseismic pore water pressure changes in deep confined aquifers and meteoric pore water pressure changes in shallow unconfined aquifers.

Laboratory of Geothermics, Kyushu University, carried out repeated gravity measurements at some geothermal power plants in Kyushu. Ehara and Nishijima (2004) suggested that the repeated gravity measurement is an effective technique to detect the recharge of fluid to geothermal reservoir. Therefore it can contribute to the discussion of sustainable development of geothermal energy. Nishijima et al. (2005a) and Saito et al. (2006) detected a gravity decrease of about 250 micro-gal in the production zone of Hatchobaru Geothermal Power Plant. There were characteristic patterns of the gravity change in the geothermal fluid production process. In other words, a rapid decrease of gravity immediately follows the commencement of geothermal power plant before the decrease becomes gradual. According to the inversion result of gravity changes from 1994 to 2000, the geothermal reservoir pressure is estimated to have decreased by more than 1.0 Mpa.

5.5.3 Gravity Changes Associated with Sea Level Variation

Ocean bottom pressure (OBP) data observed at two stations off Sanriku were compared with ocean tide models, altimetry, and barotropic signals from ocean models (Matsumoto et al., 2006). Tidal signals observed show that recent ocean tide models are of accuracy better than 1.3 cm in terms of

RMS errors of vector differences for eight principal constituents. The comparison between the OBP data and a wind-driven ocean model as well as a pressure driven model suggested that the combination of the both models can reproduce the observed non-tidal ocean mass variability better, in particular, at the periods shorter than 30 days.

Nawa et al. (2003) and Nawa and Suda (2003) observed sea level variations in seismic normal mode band with a tide gauge and GPS on the sea ice at Syowa Station and discussed their effect on gravity and seismic observations.

5.6 Gravity Survey in Japan

5.6.1 General

In order to reveal the brief feature of gravity anomalies, GSJ/AIST conducted gravity surveys at about 3500 stations in Chugoku-Shikoku area from 2003 to 2006, at about 200 stations in and around Usu and Iwate Volcanoes from 2003 to 2005, and at about 436 stations in and around the eastern area of Itoigawa-Shizuoka Tectonic Line (ITL) (Komazawa, 2004) in October 2002 and December 2003, respectively. The data from East Kyushu were published (Nawa et al., 2005). For the survey of ITL, 326 stations were co-located at seismic survey points.

Gravity research group in southwest Japan (2005) released a gravity database that was constructed by the group and published in 2001. More than 140 data sets collected by 37 organizations are compiled and 90,000 point data from 32 organizations are published.

In the past four years, Chubu University conducted an extensive gravity survey in the areas where the gravity data were voids or sparsely distributed. This survey was executed as a cooperative work with Ehime University. The areas were extended from Kyushu to Northeast Honshu and about 20,000 data were recently supplemented to their gravity database.

JHOD conducted gravity surveys in the vicinities of Fukutoku-Okanoba Submarine Volcano located in the volcanic front of the Izu-Ogasawara arc in 1999. The observation result suggests that Fukutoku-Okanoba is a part of an active submarine caldera accommodating magma beneath it (Onodera et al., 2003).

5.6.2 Hokkaido Area

Geological Survey of Hokkaido (GSH) performed gravity surveys around Furano Active Fault Zone, Central Hokkaido (Hokkaido Government, 2003). In order to study a relationship between the gravity anomaly field and the active fault structure, they conducted a regional survey around Furano Basin and a profile survey along the seismic observation line across the fault. Gravity stations number 110 for the regional survey and 135 for the profile survey. Tamura et al. (2003) produced a regional Bouguer anomaly map, estimated a two-dimensional (2-D) subsurface structure along the profile across the fault, and found the existence of a few steep gravity gradients originated from the reverse faulting.

GSH also carried out gravity surveys at 298 stations along three profiles across Shibetsu Active Fault Zone, East Hokkaido (Hokkaido Government, 2004). As a result, they detected the existence of gentle gradients in gravity anomaly that is caused by the basement subsidence, but did not find any feature corresponding to a thrusting fault structure. In addition, GSH conducted gravity surveys at 161 stations along two profiles across Tokachi-Heiya Fault Zone, East Hokkaido (Hokkaido Government, 2005).

5.6.3 Honshu Area

ERI and Meteorological Research Institute (MRI) carried out the first absolute gravity measurement on the top of Mt. Fuji in August 2003 (Okubo et al., 2005). The most difficult part of this campaign was, without doubt, the safe transport of the delicate FG5 components (Laser, Interferometer, Dropping Chamber, etc.). The harsh weather environment in the summit of Mt. Fuji (annual average wind speed of 20 m/sec, snowfall during September through May, rainy season in June, and so on) only allows them to plan the campaign in July/August - the highest season for the climbers/tourists to Mt. Fuji. Careful consideration of severe vibration exceeding 1G during transportation and low barometric pressure (2/3 of that on the sea level) enables them to run the FG5 successfully: 4959 drops with a standard deviation of only 14.2 micro-gal. After applying geophysical corrections (barometric correction/ocean tide/polar motion), they obtained 978,867.6569 ± 0.00020 [mgal] at 130 cm above the floor of Japan Meteorological Agency (JMA) weather station. Relative gravity measurement between the absolute gravity point and the Kengamine Triangulation Point (KTP) gives them g=978,865.398 ± 0.003 [mgal] at KTP. The measurement will be used to study long term volcanism of Mt. Fuji and tectonics of the Philippine Sea/Eurasian Plate boundary through monitoring the time change of gravity.

To reveal a possible active fault in Nobi Plain, Central Japan, Nagoya University conducted a dense gravity survey. About 1400 newly obtained data were supplemented to their gravity database.

Chubu University conducted gravity surveys in Honshu Area. The surveyed areas include Atera Fault and its vicinity, Chubu District, wide areas in Kanto District, Niigata Plain and its vicinity, Niigata Prefecture, the surrounding area of the seismic source region of the 2004 Mid Niigata Prefecture earthquake, Aizu Basin, Fukushima Prefecture, Shonai Plain, and Yamagata Prefecture.

Kusumoto et al. (2004) carried out a microgravity survey across the estuary of Fuji-kawa River in Shizuoka Prefecture in order to get the information on the shallow subsurface structures of Fuji-kawa Fault System (active faults), and identified the location of Iriyamate Fault as one of

Fuij-kawa Fault System from the discontinuity of the Bouguer gravity anomalies derived from the survey.

Tanaka et al. (2004) revealed a subsurface structure under a basaltic monogenetic volcano near the southern part of Atera Fault. They estimated from a 3-D gravity inversion and reflection survey results that the volcanic vents (or fissures) were along the line of 1-1.5 km southwest of Atera Fault. Tanaka et al. (2005) carried out a precise gravity survey at the southern tip of Atera Fault as an additional survey by Tanaka et al. (2004). The fault feature in the Dendahara study area is different from the common features found in the Atera Fault area in terms of strike, dipping direction, bifurcation, and so on. They suggested that a high density material (basalt dyke or alike) caused such peculiar characters. However, Fig.4 is misprinted. The correct one can be found on the following URL: (http://www.tries.jp/~tanaka/).

Tanaka, K. et al. (2006) carried out gravity surveys at four active volcanoes in Tohoku District, Northeast Japan. High Bouguer anomalies are observed at three strato-volcanoes of Iwaki, Iwate, and Bandai. This suggests the intrusion of volcanic rocks with higher density into the basement of these volcanoes. No noticeable anomaly was observed for Akita-Komagatake Volcano.

Along the Horikawa-Oguraike and Kuzebashi seismic reflection and refraction profiles in Kyoto Basin, Inoue et al. (2004) conducted gravity measurements at 50 - 300 m intervals, and estimated the sediment density in the basin.

Akamatsu and Komazawa (2003) and Akamatsu et al.(2004a; 2004b) estimated basement structure of Osaka, Kyoto and Nara Basins using their own gravity data as well as pre-existing gravity database published. The results show that the boundary between Kyoto and Nara Basins is deviated by about 12 km between the topographic boundary and the estimated model. Moreover, the shape and size of the boundary are significantly different in some areas between the topographic boundary and the estimated model. In this area, the horizontal-to-vertical spectral ratio (H/V) derived from microseisms correlates well with that corresponding to the depth of gravity basement (Akamatsu and Komazawa, 2003; Akamatsu et al., 2004a). The same characteristics are also found in the ground vibration structure in intra-mountain basin (Akamatsu et al., 2004b).

DPRI and GSJ/AIST has completed precise gravity survey densely for investigating the structure around Arima-Takatsuki Fault System, which is one of the main active faults in Kinki District, West Japan. It is found that graben-type structure does not correspond simply to the known active fault, but, extends further along the no-more-active segment in the eastern part of the fault system (Akamatsu et al., 2006).

5.6.4 Shikoku and Kyushu Area

Kagoshima University carried out two gravity surveys in South Kyushu. In 1997 two

Northwestern Kagoshima earthquakes (M6.5 and M6.7) occurred. Miyamachi et al. (2004) measured gravity at 782 sites in the aftershock area (30 km x 30 km) and created gravity anomaly maps. They found that aftershocks occurred in the low gravity anomaly area but no aftershocks occurred in the high gravity anomaly area even if the area was located in the central part of aftershock area.

Miyamachi et al. (2006) carried out a highly-dense gravity survey at 323 sites in Amami-Oshima Island, Kagoshima, in order to study the detailed gravity anomaly distribution. The results show that Amami-Oshima Island has the positive anomalies between + 32 and + 66 mgal, with a trend in the direction of NE to SW parallel to Ryukyu Trench. The trend-corrected gravity anomaly field also indicates that the northern and southern areas in the island have negative gravity anomalies.

Chubu University conducted gravity surveys in Kyushu Area. The surveyed areas consist of Osumi and Satsuma Peninsulas in the south, the northwest part, and isolated islands in the west (Koshiki-jima, Iki, Hirado, Ikitsuki-jima, and Azuchi-Oshima Islands and the Goto Island Chain).

Laboratory of Geothermics, Kyushu University carried out a dense gravity survey around an active fault, namely, Kego Fault. They measured gravity at 1259 points using Scintrex CG3 and CG3M gravimeters. The high gradient zone of Bouguer anomaly was detected along Kego Fault. They suggested that the detailed Bouguer anomaly map can be utilized for making the earthquake hazard map (Nishijima et al., 2005b; Nishijima et al., 2005c; Fujimitsu et al., 2006). Saibi et al. (2005) carried out a gravity survey at Obama Geothermal Field, West Kyushu. They applied an analytic signal method of Euler deconvolution to the Bouguer anomaly map, and estimated the underground structure (Saibi et al., 2006a; 2006b; 2006c).

Nozaki et al. (2005) carried out a microgravity survey for engineering purposes along a breakwater of the box caisson type of 890-m-long, off-shore Kochi, Shikoku. The survey was performed for the first time at least in Japan, aimed at detecting the cavities within caisson chambers that might be arisen below the overburden concrete slab with 3-m-thick and might reduce the stability of the breakwater. In the survey, a technique of the synchronized micro-gravimetry is introduced, employing two profile lines: one is the measurement line and the other is the reference line. The separation between the two profile lines is 10 – 15 m. The spacing of the gravity stations is settled at every 2 m interval for each profile line. The total number of stations amounts to 892 (446 for each line). Gravity measurements were performed by using a couple of Scintrex CG3M meters, the sampling rates being synchronized within one second to evaluate the coherent noises. The results of the survey were critically evaluated over a 200-m calibration interval where the top of filled-in sands for each chamber is monitored. The results show that gravity lows corresponding to the locations of relatively large cavities with heights of more than about 3 m, whose horizontal section is 4 m x 4 m, are successfully detected by microgravity anomalies with the amplitudes of 0.01 mgal to 0.05 mgal over the anomalous intervals of 20 - 40 m. The authors emphasize that this kind of microgravity survey method provides a quite effective tool for non-destructive detection of the cavities.

5.7 Gravity Survey in Foreign Countries

ERI and China Seismological Administration (CSA) (Institute of Seismology and Yunnan Earthquake Bureau) jointly carried out absolute/relative gravimetric campaign for 1 -14 September 2005 in Yunnan Province, China. They established a reliable gravity network consisting of 4 absolute and 40 relative points. The purpose of this project is to detect gravity changes caused by earthquakes in the area and by geodynamic processes of Tibetan Plateau through repeated measurements for a long period.

Southeast Alaska is undergoing a rapid ice-melting and land uplift due to the effect of global warming in the last three hundred years. The corresponding crustal deformation caused by the post-glacial rebound (PGR) has been clearly detected by modern geodetic techniques, e.g., GPS and tidal gauge measurements (Larsen et al., 2005; Sato et al., 2006). The geodetic deformation provides us useful information in evaluating ice-melting rate, effect of global warming, and even the viscosity beneath the crust. For this purpose, integrated geodetic observation, especially including gravity measurement, is very important. Therefore, to detect the crustal deformation caused by PGR and to study the viscoelastic structure of the Earth in Southeast Alaska and to refine the viscoelastic model derived by Larson et al. (2005), a joint team of Japanese and U.S. researchers has begun a four-year project of GPS, Earth tide, and absolute gravity measurements in 2005, called ISEA (International geodetic project in SouthEastern Alaska).

As a partner, ERI joined in the project and performed the first absolute gravity observation for 3 -18 June 2006 (Sun et al., 2006a). During the 2006 observation campaign, they established an absolute gravity network comprising of five sites in an area of about 100 km x 100 km around Juneau, i.e. (1) Bartlett Cove at Gustavus, (2) Russell Island, (3) Hains Fairground at Hains, (4) UAS Egan Library at Juneau and (5) Mendenhall Glacier Visitors Center at Juneau, Alaska. Sasagawa et al. (1989) made a gravity observation in 1987 at Hains and revealed a gravity decrease of about 100 micro-gal for 19 years. A typical occupation recorded a set of 100 single measurements every 30 minutes. At each site data were collected over a 48 - 62 hour period. The final results show that the precision of observation is pretty high, less than one micro-gal for all the five sites. These gravity data will be of fundamental importance when studying related geophysical studies on the southeast Alaska area.

Gravity tide observation using a Scintrex CG3M gravimeter was started in the campus of University of Alaska, Southeast to provide precise corrections for the effect of ocean tide loading, which are the keys to increase the observation accuracy of absolute gravimetry (Sato et al., 2006c).

Laboratory of Geothermics, Kyushu University analyzed existing Bouguer anomaly data for northwest Java Island, Indonesia. They made some filtered maps and compared them with the heat flow data. A very high heat flow area corresponds to the fault zone mapped from the gravity data (Suryantini et al., 2006).

The disaster caused by the earthquake (M7.0), occurred near Lijiang Basin in 1996, was very large and was distributed irregularly. DPRI and GSJ/AIST conducted a gravity survey in Lijiang and Hochin Basins in Yunnan Province, China, in the summers of 1998, 1999, 2002, 2003 and 2004 in cooperation with Seismological Bureau of Yunnan Province. A gravity-basement-model of the basins was obtained from gravity anomaly analysis. The model shows the elongated feature in the north and the south, corresponding to a big graben structure of the basins. The determined thickness of the sedimentary layer exceeds 2 km. The shape of the gravity basement is in accordance with that of the results of micro-tremors and seismic-refraction exploration. But there exists no clear structure with a NE-SW gradient, suspected from the movement of active Lijiang-Jianchan Fault (Komazawa et al., 2005).

5.8 Marine Gravimetry

GSJ/AIST has been conducting marine gravity surveys since 1974 as a part of the geological mapping program for the continental margin around the Japanese Islands. The survey vessel “Hakurei-maru No.2” has been used since 2000. The cruises from 2003 through 2006 are listed in Table 1.

The gravity measurements were conducted using the same straight-line sea gravimeter, LCR SL-2, in all the cruises. Free-air and Bouguer anomaly maps have been published as appendices of "Marine Geology Map Series" at a scale of 1:200,000 (Geological Survey of Japan, 2003a).

Table 1. Cruises for marine gravimetry by the GSJ from 2003 to 2006.

Cruise ID	Cruise period	Survey Area
GH03	May. - Jun. 2003	South of Hokkaido
GH04	July. - Aug. 2004	South of Hokkaido
GH05	July. - Aug. 2005	Northwestern Pacific east of Tohoku
GH06	Aug. - Sep. 2006	Southwest of Hokkaido

JHOD carried out marine gravity surveys using three survey vessels “Shoyo” (3128 gross tons), “Takuyo” (2600 gross tons) and “Meiyo” (550 gross tons) during the period of FY 2002 to FY2005. These vessels are equipped with the sea gravimeter Bodenseewerk KSS-31 or KSS-30. The cruises from April 2002 through March 2006 are listed in Tables 2, 3 and 4 (Hydrographic and

Oceanographic Department, 2003; 2004).

Table 2.Cruises of ”Shoyo” for marine gravity surveys conducted by JHOD during the period from April 2002 to March 2006

Cruise Period	Survey Area
May – Jun.2002	Minami-Hiyoshi Kaizan
May – Jun.2002	Kita-Fukutoku Tai
Aug. – Sep. 2002	Offing of Miyagi
Jul. 2003	Offing of Kii-Tokai

Table 3. Cruises of “Takuyo” for marine gravity surveys conducted by JHOD during the period from April 2002 to March 2006

Cruise Period	Survey Area
Jun. – Jul. 2002	Kita-Fukutoku Tai

Table 4. Cruises of “Meiyo” for marine gravity surveys conducted by JHOD during the period from April 2002 to March 2006

Cruise Period	Survey Area
Jun. – Jul. 2003	Offing of Simane
Apr. – May 2004	Wakamiko
Jan. – Feb. 2006	Kikai caldera

A ship-borne gravity survey on board the icebreaker “Shirase” has been continuously conducted since JARE-27. Konishi et al. (2006) recently processed the data from JARE-34 to JARE-46 and obtained free-air gravity anomalies. They also reprocessed the data sets since JARE-27, which improved the quality of signals, in particular, in the long wavelength signals.

Acquisition of various global data for marine geophysical exploration such as gravity and geo magnetic data has increased substantially in recent decades. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) operates eight research vessels for 200 days every year and has been obtaining dense geophysical data, especially in the Izu-Bonin-Mariana and the Mid-Atlantic Ridge regions.

Deschamps and Fujiwara (2003) analyzed bathymetric and magnetic data along three distinct spreading segments in Mariana Basin together with motions by GPS and indicated the existence of highly asymmetric spreading processes. Deschamps et al. (2005) described in detail the formation process of the oceanic crust in Mariana Basin from Wadatsumi side-scan sonar images, gravity and geomagnetic data collected at the sea surface.

Mid-Atlantic Ridge around Fifteen-Twenty Fracture Zone is unique in that outcrops of lower crust and mantle rocks are extensive on both flanks of the axial valley walls over an unusually long distance along the valley axis, indicating a high ratio of tectonic to magmatic extension. Based on newly collected multi-beam bathymetry, magnetic, and gravity data, Fujiwara et al. (2003) investigated crustal evolution of this unique section of Mid-Atlantic Ridge over the last 5 Ma.

To characterize the crust-mantle boundary (petrogical "Moho") and to find evidence of ophiolite model, Matsumoto et al. (2003) reported the lithology and the development process of the oceanic crust. They carried out geological and geophysical studies of Atlantis Bank core complex located at the eastern margin of Atlantis-II active transform in Southwest Indian Ridge (SWIR) using deep sea submersibles and remotely operated vehicles.

Mjelde et al. (2007) has corrected and imaged crustal structure across Jan Mayen Ridge, North Atlantic with full constraints by using gravity anomaly data.

Underway geophysical observation over the easternmost SWIR was carried out on board the research vessel "Yokosuka" by JAMSTEC as an international cruise under the InterRidge Program. Off-axis bathymetry, gravity, and magnetic data obtained suggest that spreading at the ultra-slow SWIR is dominated by large offset, asymmetric normal faulting, with significant flexural uplift of the footwalls (Cannat et al., 2003).

Ocean bottom gravity measurements were carried out in Seto Inland Sea by using a gravimeter jointly developed by ERI and Tohoku University (Joshima et al., 2006).

5.9 Data Handling and Gravity/Geoid Maps

GSI has been conducting GPS survey at benchmarks over isolated islands in order to fill-in the data voids in a hybrid geoid model, from a gravimetric geoid model and GPS/leveling geoid height data, GSIGEO2000 (Kuroishi et al., 2002), which was published in 2002 mostly for the major islands of Japan by GSI as the official national geoid model. As of 1 December 2005, GSIGEO2000 version 4 was published, appending the geoid information newly for 50 isolated islands to the original model.

GSI has also conducted GPS survey at benchmarks in the edges of 16 peninsular areas that are located outside of the coverage of the GPS/leveling data used in the development of GSIGEO2000. The preliminary results obtained in six out of these 16 areas show that the discrepancies of the geoid heights between GSIGEO2000 and GPS/leveling data reach about 5 cm at maximum.

Nomura et al. (2006a) evaluated effects of the height revision of GEONET site coordinates associated with the replacement and re-installment of the antenna for GEONET sites, on GSIGEO2000 in terms of geoid height. In the development of GSIGEO2000, the geoid heights of GSIGEO2000 were highly constrained with those of the GPS/leveling data, whose ellipsoidal heights were determined by fixing all 108 GEONET sites, available at the time of GPS observation, at the then-employed official coordinates in ITRF94 epoch 1997.0. The changes of the GPS/leveling geoid heights yielded by the height revision were estimated: the mean and standard deviation about the mean are -1.9 and 1.7 cm, respectively and the maximum modulus is less than 7 cm. The effects are evaluated as minor in the application of GSIGEO2000 to the height conversion from GPS derived ellipsoidal heights to corresponding orthometric heights within its precision.

GSI conducted gravity survey in Yaku-shima Island and GPS survey at benchmarks in Yaku-shima and adjacent islands, and computed a hybrid geoid model for that area. Yaku-shima Island is located on the volcanic front between Ryuku Trench and Okinawa Trough and has a rugged terrain of an area of about 500 km^2 with a highest peak of about 2000 m. Since the land gravity data used in the development of the gravimetric geoid model are limited along the coast (only at 12 points), the geoid model is not expected to recover the geoid precisely at short wavelengths. GSI made gravity survey at 28 points inland and the GSJ provided 190 points of land gravity in Yaku-shima Island, so that Kuroishi et al. (2004) developed a much improved gravimetric geoid model by using the same methodology as that employed in the JGEOID2000 development. The improved model reveals that a geoidal mound exists on the eastern end and the geoid has a tilt to the east, toward the trench axis. GSI computed a hybrid geoid model for Yaku-shima, Tanega-shima, Kuchinoerabu-jima, and Satsuma-Iwo-jima Islands by combining the improved gravimetric geoid model with 52 data of GPS/leveling geoid heights and the model is evaluated to have accuracy comparable to GSIGEO2000.

GSJ/AIST published eight detailed complete Bouguer anomaly maps at 1:200,000 scale, "Gravity Map Series", Karatsu, Miyazaki, Kagoshima, Yaku-shima, Nagasaki, and Yamaguchi Districts, from about fifty thousands of data as part of the gravity mapping program of the Japanese Islands (Geological Survey of Japan, 2003b; 2004a; 2004b; 2005; 2006a; 2006b).

GSJ/AIST carried out gravity survey in Fukui Plain from 2000 to 2002 for investigation of underground structure and active faults, and the gravito-tectonic map was published (Komazawa, 2006).

Heliani et al. (2003) determined a precise Indonesian gravity field model from surface gravity, altimeter data and a digital terrain model. Because the available Indonesian land gravity data were limited, they employed supplemental land gravity data simulated by using a digital terrain model (Heliani et al., 2004).

Ueda (2003; 2005) compiled Bouguer gravity anomaly maps of the Japanese Island arcs and its adjacent seas. Sasahara (2005a; 2005b) and Sasahara et al. (2006a; 2006b) determined a new precise marine geoid model. The model is given on a grid of 1´ x 1´ in the area 15ºN - 50ºN and 120ºE - 160ºE, compounded from a global geopotential model (for long wavelength), altimetric gravity data (for middle wavelength), and land and ship-borne gravity data (for short wavelength).

5.10 Gravity Data Analysis

Fukunaga et al. (2004) analyzed the gravity database for southwest Japan for studying the geometry of the Moho discontinuity interface.

Kudo et al. (2004) developed a statistical method to interpret the spatial distribution of topographic lineaments in Chugoku Area by employing the standard deviations of variations of Bouguer anomalies as an index of gravity anomaly roughness.

Shichi et al. (2005) analyzed characteristic gravimetric features of Kyushu Area by applying both gravity databases constructed by Gravity Research Group in Southwest Japan (2001) and by the Geological Survey of Japan (2000).

5.11 Theoretical Studies on Geoid and Gravity Field

Kuroishi (2003) and Kojiroi and Kuroishi (2004) presented brief reviews on gravity, height systems and geoid and gave introductory reports of the vertical datum of Japan as part of the Japan Geodetic Coordinates 2000.

Kuroishi and Denker (2003) investigated the area around Japan regarding the handling of ship and altimetric gravity data and its effect on local geoid models. They prepared different data sets based on those data and their hybrid ones, and considered the classical Stokes kernel and its modification in the geoid computation. The results showed that different adjustments and combinations of ship and altimetric gravity data could produce biases larger than 1 m in geoid height and tilt the geoid models by more than 1 parts per million (ppm), and they pointed out the importance of a study of the spatio-frequency characteristics of the ocean gravity field models.

Kuroishi (2004) reviewed a then-latest gravimetric geoid modeling for Japan, JGEOID2000 (Kuroishi, 2001) and its improvement study and presented expectation of the dedicated satellite missions for enhancement of the geoid modeling study.

Kuroishi and Keller (2005) developed a semi-discrete wavelet analysis/reconstruction method for localizing 2-D signal components in the spatio-frequency domain. They employed 2-D Halo wavelets and demonstrated the effectiveness of the method in screening data as a locally-adjustable filter. They successfully applied the method to a combination of marine gravity data and an altimetric gravity model, KMS02 and yielded an improved gravimetric geoid model for Japan, JGEOID2004. Compared with 816 GPS/leveling benchmarks over Japan, JGEOID2004 exhibited significant improvement over a previous model, JGEOID2000. The application of the semi-discrete wavelet method and inclusion of newly acquired terrestrial gravity data supplemented to the data gaps of JGEOID2000 in inland sea and on the main islands of Japan, effectively removed substantial localized errors, which were due to systematic errors of the marine gravity data as well as data gaps.

Nozaki (2006) proposed a new concept of the generalized Bouguer anomaly (GBA), which is defined upon the datum level of an arbitrary elevation. The subject of GBA is the generalization of the classical Bouguer anomaly used in geophysics to study the subsurface density structures. The classical Bouguer anomaly is a good contrast to the modern Bouguer anomaly defined as an extension of the geodetic gravity anomaly. By introducing a new concept of the specific datum levels so that GBA is not affected by the topographic masses, he shows the equations of GBA upon the specific datum levels become free from the assumed topographic density and/or the terrain correction and derives an approximate equation for estimating the density. Finally, he gives a method to compute a Bouguer anomaly on the geoid by transforming GBA at the specific datum level to the level of the geoid. These procedures yield a new method for obtaining a distribution of the classical Bouguer anomaly, which is free from the density assumption. He remarks that GBA upon the density-free datum level yields the gravity disturbance and that its equation has an intimate tie to the fundamental equation of physical geodesy. Despite that the figure of the Earth is not the main subject of such a generalization, this approach gives new perspectives to the theory of physical geodesy, which totally mediates between the geophysical and geodetic gravity anomalies.

Sun (2004a) investigated some discretizations of the Poisson integral. A single mean scheme is proposed to overcome the disadvantage of the double mean scheme. Basically the single mean scheme is the same as the double one, but it is numerically simple since it greatly reduces numerical work. Comparison between the point and mean schemes shows that, for a limit topographical grid size, the point discrete scheme presents a serious theoretical problem, i.e., it greatly devalues gravity on geoid, and even gives suspicious result in an extreme case. Sun (2004a) found that difficulty of dealing with the Poisson integral is due to behaviors of the Poisson kernel. Numerical analysis indicates that the diagonal values for the point scheme on a 5’ x 5’ division are much larger than those of the mean scheme. Therefore, a careful consideration of constructing matrix coefficient of the discrete system of the Poisson integral is much more important. A basic principle of a valid discretization for any integration is that the discrete kernel function value should well-approximate the true value on each grid; otherwise discretization will bring a serious error to results.

Sun (2003; 2004b) presented an asymptotic theory for calculating coseismic potential/geoid and gravity changes, as an approximation of the dislocation theory for a spherical Earth (Sun and Okubo, 1993). This theory is given by a closed form of mathematical expressions, so that it is mathematically simple and can be applied easily. Moreover, since the asymptotic theory includes sphericity and vertical structure effects, it is physically more reasonable than the flat-Earth theory. A comparison between results calculated by using three dislocation theories (the flat-Earth theory, the theory for a spherical Earth and its asymptotic solution) shows that the true coseismic geoid changes are approximated better by the asymptotic results than those of a flat-Earth. Numerical results indicate that the spherical effect is obviously large, especially for a tensile source on a vertical fault plane.

Sun and Okubo (2004a; 2004b) proposed a concept of truncated geoid and gravity changes together with their expressions for investigating coseismic deformations. They carried out numerical investigations to observe whether or not coseismic geoid and gravity changes are detectable by satellite gravity missions. Results of an individual harmonic degree or a summation to interested degrees are compared with the expected errors of the gravity missions, assuming a seismic source equivalent to the fault size of the 1964 Alaska earthquake (Mw9.2). Corresponding coseismic deformations indicate that both the gravity and geoid changes are about two orders larger than the precision of a dedicated satellite gravity mission, GRACE. Based on these results, the minimum magnitudes of earthquakes detectable by GRACE are derived. They concluded that coseismic deformations for an earthquake with a seismic magnitude above M7.5 (for the tensile sources) and M9.0 (for the shear sources) can be detected by GRACE. Finally, a case study on the 2002 Alaska earthquake (M7.9) showed that the coseismic geoid and gravity changes are at or below the error level of GRACE, and are difficult to detect.

Tanaka, T. et al. (2006) introduced a new method to compute global postseismic deformation (PSD) in a spherically symmetric, self-gravitating viscoelastic Earth model. Previous methods are based on simplified Earth models that neglect compressibility and/or the continuous variation of the radial structure of Earth. This is because the previous mode summation technique cannot avoid intrinsic numerical difficulties caused by the innumerable poles that appear in a realistic Earth model that considers such effects. In contrast, the proposed method enables both of these effects to be taken into account simultaneously. They carried out numerical inverse Laplace integration, which allows evaluation of the contribution from all of the innumerable modes of the realistic Earth model. Using this method, a complete set of Green’s functions is obtained, including functions of the time variation of the displacement, gravity change, and the geoid height change at the surface for strike-slip, dip-slip, horizontal, and vertical tensile point dislocations. As an Earth model, they employed the preliminary reference Earth model (PREM) and a convex viscosity profile. Further, they investigated the effects of fine layering of the viscoelastic structure and compressibility on a time-series of PSD using the Green’s function for a dip-slip fault. The result indicates that the effect of increasing number of layers is saturated at several tens of layers even when compressibility is taken into account and that the effect of compressibility is detectable with modern observation techniques for a shallower large earthquake (~Mw 8). As an application, the PSD due to the 2004 Sumatra-Andaman earthquake (Mw9.3) is estimated. They showed that the rate of postseismic vertical displacement and gravity change is possibly detected in the far field where the epicentral distance exceeds 400 km.

5.12 Space Gravimetry

Kaula's rule of thumb has been used in producing geopotential models from space geodetic measurements, including the most recent models from a satellite gravity mission, CHAllenging Mini-satellite Payload (CHAMP). Although an alternative regularization method by introducing a number of regularization parameters was proposed in 1992, no numerical tests have ever been conducted. Xu et al. (2006a) have compared four methods of regularization for the determination of geopotential from precise orbits of COSMIC satellites through simulations: Kaula's rule of thumb, one-parameter regularization and its iterative version, and multiple-parameter regularization. The simulation results have shown that the four methods can indeed produce good gravitational models from the precise orbits of centimeter level. The three regularization methods perform much better than Kaula's rule of thumb by a factor of 6.4 on average beyond spherical harmonic degree 5 and by a factor of 10.2 for the spherical harmonic degrees from 8 to 14 in terms of degree variations of RMS errors. The maximum component-wise improvement in RMS can be up to a factor of 60. The simplest version of regularization by multiplying a positive scalar with a unit matrix is sufficient to better determine the geopotential model. Although multiple parameter regularization is theoretically attractive and can indeed eliminate unnecessary regularization for some of the harmonic coefficients, we found that it only improved its one-parameter version marginally with this COSMIC example in terms of mean squared error.

However, if space geodetic measurements are assumed to be heteroscedastic with different unknown variance components, all regularization techniques may not be proper to apply, unless techniques of variance component estimation are directly implemented. Although variance component estimation techniques have been proposed to simultaneously estimate the variance components and provide a means of regularization, the regularization parameter is treated as if it were also an extra variance component. As a result, Xu et al. (2006b) assume no prior information on the model parameters and do not treat the regularization parameter as an extra variance component. Instead, they first analyze the biases of estimated variance components due to the regularization parameter and then propose bias-corrected variance component estimators. The results have shown that they work very well. Finally they propose and investigate through simulations an iterative scheme to simultaneously estimate the variance components and the regularization parameter in order to eliminate the effect of regularization parameter on variance components and the effect of incorrect prior weights or initial variance components on the regularization parameter.

5.12.1 Lunar and Planetary Gravimetry

Study of the lunar gravity anomaly has not been straightforward since direct tracking data of lunar satellites are available only at the nearside of the Moon. In such a case, direct inversion of the line-of-sight acceleration data into surface mass distribution has several merits: (1) high resolution attainable without relying on artificial constraints, and (2) short computation time by estimating regional parameter sets stepwise. Sugano and Heki (2004a) processed the line-of-sight acceleration data of the Lunar Prospector extended low-altitude mission after confirming the validity of the method using synthesized data. They obtained a gravity anomaly map of the lunar nearside with resolution as high as 0.8º x 0.8º, equivalent to 225th degree/order of spherical harmonics, with less spurious signatures than previous studies. To take advantage of the high resolution, they calculated mass deficits for 92 medium-sized craters (50 – 300 km in diameter), and confirmed that the deficits are nearly proportional to 2.5 power of crater diameter.

Sugano and Heki (2004b; 2004c; 2005) presented high-resolution Bouguer gravity anomalies of the lunar nearside after applying correction to the Lunar Prospector line-of-sight acceleration data. They investigated lithospheric thicknesses of the early Moon by comparing the gravity anomalies of craters and impact basins of various dimensions. The lithosphere was already thick enough to support craters with diameters up to 300 km in the Pre-Nectarian and Nectarian Periods. Degree of isostatic compensation of larger impact basins suggested lithospheric thickness of 20 – 60 km at that time, which depended more on localities rather than on age differences.

5.12.2 Satellite Gravity Missions

GSI initiated study on gravity field recovery from data obtained by satellite gravity missions, CHAMP and GRACE, in cooperation with the Goddard Space Flight Center, NASA of USA. One of its main purposes is to determine the static gravity field regionally in the area around Japan for enhancing improvement of gravimetric geoid modeling in terms of the absolute locations. Kuroishi and Munekane (2005) processed CHAMP science orbit data for global gravity recovery and discussed the use of regularization and de-aliasing treatment. Kuroishi et al. (2005; 2006a; 2006b) have been working with GRACE data for recovery of the gravity field regionally in the area around Japan as well as globally. The resulting monthly global gravity models, after smoothed with a Gaussian isotropic filter, represented seasonal gravity changes over major continental river basins and indicated the necessity of improved de-aliasing over the oceans for practicing the geoid model refinement at long wavelengths for Japan.

Yamamoto et al. (2005) simulated the recovery of a gravity field from four-week simulated data and investigated the relation between the recovery precision and the ground track. They showed that the GRACE ground track in 2003 was in good condition for four-week gravity field recovery, but it can become worse as the orbit altitude decays. Their simulated results have shown that tracks at the altitudes of 473, 448, 399, 350 and 337 km could result in insufficient spatial resolutions, even for gravity field recovery up to degree 30.

Sugano (2006) extended the line-of-sight acceleration data analysis described in 5.12.1 to GRACE gravity field recovery. He applied this method to GRACE Level 1B data. The model for Lunar Prospector was adapted to low-low-satellite configuration of GRACE. This extension is easily achieved thanks to the simplicity of the adopted model. Among the GRACE Level 1B data, he employed KBR range acceleration data as line-of-sight acceleration. Accelerometer data combined with Star Camera data was used to correct non-gravitational acceleration contained in the range acceleration data. GPS navigation data was used to obtain information of the satellites positions after interpolation to 5 second interval. A gravity map on a 3° x 3° grid is obtained using a month of data.

Coseismic deformations observed on the Earth surface or modeled by conventional dislocation theory cannot be compared directly with those observed by gravity satellite missions because of the spatial resolution limit of the missions and the signal attenuation of the gravity field. Coseismic deformations in the spectrum domain should be considered instead. For this purpose, the dislocation theory (e.g., Sun and Okubo, 1993) for a spherical Earth model can be used because it is expressed in terms of spherical harmonics. Sun and Okubo (2004a; 2005) derived analytical expressions of degree variances of the coseismic geoid and gravity changes for shear and tensile sources and calculated for three real earthquakes. Those results are compared with expected errors of GRACE to elucidate whether or not coseismic geoid and gravity changes are detectable by gravity satellite missions. They investigated behaviors of the degree variances for four independent seismic sources and found that both the gravity and geoid changes are nearly two orders of magnitude larger than the precision of the gravity missions in low harmonic degrees. Based on these results, they concluded that coseismic deformations for an earthquake with a seismic magnitude above M7.5 are expected to be detected by GRACE.

Sun et al. (2006b) presented a new approach to calculate dislocation Love numbers using observations of a satellite gravity mission (e.g. GRACE). The necessary condition is that the coseismic potential change be sufficiently large to be detected by the gravity mission. Coseismic deformations for each spherical harmonic degree n are decoupled. Therefore, dislocation Love numbers of degree n can be determined independently. The determinable maximum harmonic degree n depends on the seismic size, source type, magnitude, and the accuracy of a satellite gravity mission. For an arbitrary seismic source, all four types of dislocation Love numbers can be determined using data from only one seismic event because all deformation components are involved together. Only the concerned dislocation Love numbers can be computed for any one of the four types of sources. To prove the validity of the method proposed in this study, a simulation test is carried out by considering a similar case to the 2004 Sumatra-Andaman earthquake (Mw 9.1). Results show that the method works well and guarantee the accuracy.

5.13 Superconducting Gravimetry

Routine observations of gravity changes have been conducted in Kyoto and Bandung, Indonesia by employing SGs. Takemoto et al. (2002) installed groundwater level-meters near the SG stations in Kyoto and Bandung and reported the effect of groundwater changes on SG observations in Kyoto and Bandung. The results revealed that in Kyoto and Bandung 1-m upheaval of groundwater level causes an increase of about 4 micro-gal increase in gravity residual. Abe et al. (2006) reported the hydrological effects on the SG observation in Bandung. They also installed soil moisture meters and the rain gauge near the SG station in Bandung and clarified that the model of soil moisture could explain about 80 % of the variations in gravity.

Fukuda et al. (2004) carried out simultaneous observations with SG and absolute gravimeter FG5 to determine the calibration factor of the SG in Bandung. They obtained the new factor with the relative precisions of 0.18%. The difference of the value to the previous one was only 0.01 micro-gal/V and was negligible.

An international program, GGP started in July 1997. Initially, GGP had been planned as a six-year program, but was extended in 2003 and officially integrated in IAG as an Intercommision Project. GGP is a project with a global network of SGs to study low frequency Earth's free oscillations, core under tone, free core resonance, long period tide and inelasticity of the Earth, coupling of the solid Earth and geophysical fluids, crustal deformation and gravity change, and so on. The Japanese GGP group organized a GGP-Japan network and established a data center at NAOJ Mizusawa. The GGP-Japan network consists of seven stations; Kyoto site operated by Kyoto University, Matsushiro site by Ocean Research Institute, University of Tokyo (ORI), Kamioka and Esashi sites by NAOJ, Ny-Alesund site in Norway jointly by NAOJ and Norwegian Mapping Authority, Canberra site in Australia jointly by NAOJ and Australian National University, and Syowa Station, Antarctica, by National Institute of Polar Research (NIPR). The GGP-Japan data center distributes not only one-minute sampling data but also high-rate sampling data.

Imanishi et al. (2002) and Tamura et al. (2005) discussed scale factor calibration of SG with absolute gravimeters. The calibration is essential to the studies of Earth tide, ocean tide loading and so on. To discuss the inelasticity of the Earth, for example, the scale factor of SG should be determined at a relative accuracy better than 0.1%. Imanishi et al. (2004) detected coseismic gravity changes at three SG sites induced by the 2003 Tokachi-oki earthquake of Mw8.3. Iwano et al. (2005) analyzed long period tides observed at Syowa Station and discussed the inelasticity of the Earth. Sato et al. (2004) discussed fluid core resonance parameters inferred from SG data. Sato et al. (2006a) and Sato et al. (2006b) analyzed SG data, and compared them with absolute gravity data, GPS data, and ice seat data at Ny-Alesund and discussed secular and seasonal changes of gravity there. They suggested that the gravity change data obtained from stable SGs can supply regional and global information on environmental change from a different view-point of meteorology and oceanography. Concerning the 2004 Sumatra-Andaman earthquake, Rosat et al. (2005) analyzed low frequency free oscillations of the Earth with high-resolution. Nawa et al. (2006a; 2006b) analyzed tsunami waves observed at Syowa Station and discussed gravity changes induced from the waves.

5.14 Air-borne Gravimetry

A new airborne (helicopter-borne) gravimeter, FGA-1 SEGAWA model, has been developed since 1998, and many practical measurements have been carried out over Kashima-Nada, Enshu-Nada, Suruga Bay and Izu-Bonin Islands (Segawa et al., 2003; Joseph et al., 2003; Segawa et al., 2005a). In the observation over Kashima-Nada, the SEGAWA model showed that the average bias difference is 0.5 mgal and standard deviation is 1.5 mgal and that this gravimeter has a potential of finding the active faults from land to sea floor (Segawa et al., 2003). In fact, in the observation over Enshu-Nada, Segawa et al. (2005a) found the gravity anomaly pattern reflecting the structure of Akaishi Fracture Zone.

One of the first significant results was the discovery of disagreement of gravity anomaly between land and sea. The amount of disagreement is as large as 15 mgal. Such disagreement was confirmed in the middle of Honshu and the neighboring Pacific Ocean (Segawa et al., 2005b).

The air-borne gravimetry survey was also extended to Izu-Bonin Island areas such as Kozu-shima, Miyake-jima and Nii-jima Islands (Joseph et al., 2003). It is known that there is an active magma activity beneath the zone between Kozu-shima and Miyake-jima. But, from the gravity anomaly, it is not clear whether or not a significant magma block large enough to affect the gravity anomaly is involved underground. Recently it has become important to make geophysical surveys in the areas of large power plants for mapping active tectonic faults for safety precautions. To this end the air-borne gravimeter has been used in the area of Sata Peninsula of Shikoku, Noto Peninsula of Ishikawa Prefecture and Wakasa Bay of Fukui Prefecture (Nishizaka et al., 2006).

Bibliography

Abe, M., S. Takemoto, Y. Fukuda, T. Higashi, Y. Imanishi, S. Iwano, S. Ogasawara, Y. Kobayashi, S. Dwipa, and D. S. Kusuma (2006): Hydrological effects on the superconducting gravimeter observation in Bandung, J. Geodynamics, **41**, 288-295.

Akamatsu, J. and M. Komazawa (2003): Vibrational characteristic of microseisms and gravity basement in Kyoto basin, Annuals of Disast. Prev. Res. Inst., Kyoto Univ., **46 B**, 929-936.

Akamatsu, J., M. Komazawa, K. Nakamura, and K. Nishimura (2004a): Gravity Basement of Kyoto and Nara basin area, Annuals of Disast. Prev. Res. Inst., Kyoto Univ., **47 B**, 871-876.

Akamatsu, J., H. Suwa, N. Ichikawa, and M. Komazawa (2004b): Bedrock structure of Kamikochi basin at the foot of Yakedake Volcano inferred from gravity anomaly and vibrational characteristics of microseisms, Annuals of Disast. Prev. Res. Inst., Kyoto Univ., **47 B**, 877-882.

Akamatsu, J., K. Nakamura, K. Nishimura, and M. Komazawa (2006): Crustal density structure estimated by using gravity data, Final Rep. Special Project for Earthquake Disaster Mitigation in Urban Areas, Ministry of Education, Culture, Sports, Science and Technology, 571-576.

Cannat, M., C. Rommevaux-Jestin, and H. Fujimoto (2003): Melt supply variations to a magma-poor ultra-slow spreading ridge (Southwest Indian Ridge 61 to 69 E), Geochem. Geophys. Geosyst., **4** (8), 9104, doi: 10.1029/2002GC000480.

Deschamps, A. and T. Fujiwara (2003): Asymmetric accretion along the slow-spreading Mariana Ridge, Geochem. Geophys. Geosyst., **4**, (10), 8622, doi:10.1029/2003GC000537.

Deschamps, A., T. Fujiwara, M. Asada, L. Montési, and P. Gente (2005): Faulting and volcanism in the axial valley of the slow spreading center of the Mariana back arc basin from Wadatsumi side-scan sonar images, Geochem. Geophys. Geosyst., **6**, 5, doi:10.1029/2004GC000881.

Ehara, S. and J. Nishijima (2004): Study on Sustainable Development of Geothermal Energy from Geophysical Monitoring of Geothermal Reservoir **-** A Case Study of Repeat Gravity Measurement -, J. Geothermal Res. Soc. Japan, **26**, 181-193. (in Japanese)

Fujimitsu, Y., J. Nishijima, and T. Hirano (2006): Densely-arranged Gravity Survey in Fukuoka City, Japan -Relation between the Subsurface Structure and the Low Temperature Hydrothermal System of Fukuoka-, Proc. 28th New Zealand Geothermal Workshop 2006, CD-ROM.

Fujiwara, T., J. Lin, T. Matsumoto, P. B. Kelemen, B. E. Tucholke, and J. F. Casey (2003): Crustal Evolution of the Mid-Atlantic Ridge near the Fifteen-Twenty Fracture Zone in the last 5 Ma, Geochem. Geophys. Geosyst., **4**, 3, doi:10.1029/2002GC000364.

Fukuda, Y., K. Shibuya, K. Doi, and S. Aoki (2003): A Challenge to the Detection of Regional to Local Scale Ice Sheet Movements in Antarctica by the Combination of In-situ Gravity Measurements and Gravity Satellite Data, in T. N. Tziavos (ed.), Gravity and Geoid 2002, 3rd Meeting of the International Gravity and Geoid Commission (IGGC), ZIDI , 243-248.

Fukuda, Y., T. Higashi, S. Takemoto, M. Abe, S. Dwipa, D. S. Kusuma, A. Andan, K. Doi, Y. Imanishid, and G. Arduino (2004): The first absolute gravity measurements in Indonesia, J. Geodynamics, **38**, 489-501.

Fukuda, Y., T. Higashi, S. Takemoto, S. Iwano, K. Doi, K. Shibuya, Y. Hiraoka, I. Kimura, H. McQueen, and R. Govind (2005a): Absolute gravity measurements in Australia and Syowa Station, Antarctica, in C. Jekeli et al. (eds.), IAG Symposia **129**, Gravity, Geoid and Space Missions, Springer, 280-285.

Fukuda, Y., S. Iwano, H. Ikeda, Y. Hiraoka, and K. Doi (2005b): Calibration of the superconducting gravimeter CT#043 with an absolute gravimeter FG5#210 at Syowa Station, Antarctica, Polar Geosci., **18**, 41-48.

Fukuda, Y., Y. Hiraoka, and K. Doi (2006): An experiment of precise gravity measurements on ice sheet, Antarctica, in C. Tregoning and C. Rizos (eds.), IAG Symposia **130**, Dynamic Planet, Springer, 88-93.

Fukunaga, M., H. Oda, and R. Shichi (2004): Topography of the Moho discontinuity estimated by column inversion of gravity anomaly data, Earth Sci. Rep., Okayama Univ., **11**, No.1, 1-5.

Furuya, M., S. Okubo, F. Kimata, R. Miyajima, I. Meilano, W. Sun, Y. Tanaka, and T. Miyazaki (2003a): Mass budget of the magma flow in the 2000 volcano-seismic activity at Izu-islands, Japan, Earth Planets Space, **55**, (7), 375-385.

Furuya, M., S. Okubo, W. Sun, Y. Tanaka, J. Oikawa, H. Watanabe, and T. Maekawa (2003b): Spatio-temporal gravity changes at Miyakejima volcano, Japan: Caldera collapse, explosive eruptions and magma movement, J. Geophys. Res., **108**, B4, 2219, doi:10.1029/2002JB001989.

Geological Survey of Japan (2003a): Geological Map East of Noto Peninsula, 1:200,000, Mar. Geol. Map Ser., 59.

Geological Survey of Japan (2003b): Gravity Map of Karatsu District (Bouguer anomalies), Gravity Map Ser., 19.

Geological Survey of Japan (2004a): Gravity Map of Miyazaki District (Bouguer anomalies), Gravity Map Ser., 20.

Geological Survey of Japan (2004b): Gravity Map of Kagoshima District (Bouguer anomalies), Gravity Map Ser., 21.

Geological Survey of Japan (2005): Gravity Map of Yakushima District (Bouguer anomalies), Gravity Map Ser., 22.

Geological Survey of Japan (2006a): Gravity Map of Nagasaki District (Bouguer anomalies), Gravity Map Ser., 23.

Geological Survey of Japan (2006b): Gravity Map of Yamaguchi District (Bouguer anomalies), Gravity Map Ser., 24.

Gravity research group in Southwest Japan (Representatives: Shichi, R. and A. Yamamoto) (2005): Construction and Publication of the Gravity Database of Southwest Japan, J. Geod. Soc. Japan, **51**, 17-32.

Higashi, T., Y. Fukuda, S. Ogasawara, and S. Takemoto (2002): Absolute Gravity Changes at the Fundamental Gravity Station (Kyoto C) in Kyoto University, Kyoto, Japan, J. Geod. Soc. Japan, **48**, 149-152. (in Japanese with English Abstract)

Higashi, T., Y. Fukuda, M. Abe, S. Takemoto, S. Dwipa, D. S. Kusuma, A. Andan, K. Doi, Y. Imanishi, and G. Arduino (2003): Determination of Absolute Gravity Values using a FG5#210 in Bandung and Yogyakarta, Indonesia, J. Geod. Soc. Japan, **49**, 177-180.

Heliani, L. S., Y. Fukuda, and S. Takemoto (2003): Precise Indonesian Gravity Field Determination from a Combination of Surface Gravity, Altimeter and Digital Terrain Model Data, in T.N.Tziavos (ed.), Gravity and Geoid 2002, 3rd Meeting of the International Gravity and Geoid Commission (IGGC), ZIDI, 243-248.

Heliani, L. S., Y. Fukuda, and S. Takemoto (2004): Simulation of the Indonesian land gravity data using a digital terrain model data, Earth Planets Space, **56**, 15-24.

Hiraoka, Y., I. Kimura, Y. Fukuda, K. Doi, and K. Shibuya (2005): Gravity measurements with the portable absolute gravimeter FG5 at Antarctica (III), Bull. Geogr. Surv. Inst., **108**, 21-27. (in Japanese)

Hiraoka, Y., I. Kimura, Y. Hiyama, M. Honda, H. Amemiya, A. Suzuki, S. Takemoto, Y. Fukuda, and T. Higashi (2006): Collaboration in Establishment of Absolute Gravity Standard Station Network in East Asia (II), J. Geogr. Surv. Inst., **110**, 19-25. (in Japanese)

Hiyama, Y., I. Kimura, and Y. Hiraoka (2003): Gravity Change at Mt. Fuji (2), 100th Meeting Geod. Soc. Japan Program and Abstracts, 147-148. (in Japanese)

Hokkaido Government (2003): A Report on the Survey for the Tokachi-Heiya Fault Zone, Furano Fault Zone and Shibetsu Fault Zone, Hokkaido, Japan, Special Issue, March 2003, 407p. (in Japanese)

Hokkaido Government (2004): A Report on the Survey for the Tokachi-Heiya Fault Zone, Furano Fault Zone and Shibetsu Fault Zone, Hokkaido, Japan, Special Issue, March 2004, 473p. (in Japanese)

Hokkaido Government (2005): Tokachi-Plain Active Fault Zone, Active fault Map and its Explanatory Text, Active Fault Map of Hokkaido, 5, 136p. (in Japanese)

Hydrographic and Oceanographic Department (2003): Data Rep. Hydrogr. Oceanogr. Obs., Ser. Astron. Geod., **37**. (http://www1.kaiho.mlit.go.jp/jhd-E.html)

Hydrographic and Oceanographic Department (2004): Data Rep. Hydrogr. Oceanogr. Obs., Ser. Astron. Geod., **38**. (http://www1.kaiho.mlit.go.jp/jhd-E.html)

Ikeda H., K. Doi, Y. Fukuda, T. Noguchi, T. Nakashima, K. Iimura, and K. Shibuya (2004): Installation of a superconducting gravimeter in Antarctica and development of its vibration-isolating mechanism and remote monitoring system, J. Cryo. Soc. Japan, **39**(8), 348-353. (in Japanese with English abstract)

Ikeda, H., K. Doi, Y. Fukuda, Y. Tamura, and K. Shibuya (2005): Installation of the superconducting gravimeter CT(#043) at Syowa Station, Antarctica, Polar Geosci., **18**, 49-57.

Imanishi, Y., T. Higashi, and Y. Fukuda (2002): Calibration of the superconducting gravimeter T011 by parallel observation with the absolute gravimeter FG5 #210 - a Bayesian approach, Geophys J. Int., **151**, 867-878.

Imanishi, Y., T. Sato, T. Higashi, W. Sun, and S. Okubo (2004): A network of superconducting gravimeters detects submicrogal coseismic gravity changes, Science, **306**, 476-478.

Inoue, N., Y. Tanaka, H. Itoh, S. Iwano, N. Kitada, Y. Fukuda, and K. Takemura (2004): Density of sediment in Kyoto Basin Inferred from 2D gravity analysis along Horikawa-Oguraike and Kuzebahi Seismic survey lines, J. Seism. Soc. Japan, **57**, 45-54. (in Japanese with English Abstract)

Iwano, S. and Y. Fukuda (2004): Superconducting gravimeter observations without a tilt compensation system, Phys. Earth Planet. Inter., **147**, 343-351.

Iwano, S., I. Kimura, and Y. Fukuda (2003): Calibration of the superconducting gravimeter TT70#016 at Syowa Station by parallel observation with the absolute gravimeter FG5#203, Polar Geosci., **16**, 22-28.

Iwano, S., Y. Fukuda, T. Sato, Y. Tamura, K. Matsumoto, and K. Shibuya (2005): Long-period tidal factors at Antarctica Syowa Station determined from 10 years of superconducting gravimeter data, J. Geophys. Res., **110**, B10403, doi:10.1029/2004JB003551.

Joseph, E.J., J. Segawa, S. Kusumoto, E. Nakayama, T. Ishihara, M. Komazawa, and H. Sakuma (2003): Air-borne gravimetry - a new gravimeter system and test results, Exploration Geophys., **34**, 82-86.

Joshima, M., T. Ishihara, K. Koizumi, N. Seama, A. Oshida, H. Fujimoto, and T. Kanazawa (2006): Measurements by ocean bottom gravimeter at Harima-Nada in Seto Inland Sea, Japan, J. Japan Soc. Mar. Surv. Technol., **18**, 17-27. (in Japanese with English abstract)

Kido, M., D. A. Yuen, and A. Vincent (2003): Continuous wavelet-like filter for a spherical surface and its application to localized admittance function on Mars, Phys. Earth Planet. Inter., **135**, 1-16.

Kimura, I., Y. Hiraoka, Y. Hiyama, S. Takemoto, Y. Fukuda, T. Higashi, S. Ogasawara, and H. Nakagawa (2004): Collaboration in Establishment of Absolute Gravity Standard Station Network in East Asia, J. Geogr. Surv. Inst., **105**, 61-70. (in Japanese)

Kobayashi, Y., S. Iwano, and Y. Fukuda (2004): Detailed Coastline Data around Syowa Station, Antarctica, and Calculation of the Oceanic Tidal Loading Effects, J. Geod. Soc. Japan, **50**, 17-26. (in Japanese with English Abstract)

Kojiroi, R. and Y. Kuroishi (2004): Introduction of Helmert orthometric heights in the vertical datum of Japan: another set of the Geodetic Coordinates 2000 of Japan, J. Japan Soc. Photogrammetry and Remote Sensing, **43** (1), 61-68. (in Japanese with English abstract)

Komazawa, M. (2004): Density structure inferred from gravity anomalies in the eastern area of the Itoigawa-Shizuoka Tectonic Line, central Japan, Earth Planets Space, **56**, 1309-1314.

Komazawa, M. (2006): Gravito-tectonic Map of Fukui District (Bouguer anomalies and gravity basement), Gravity Map Ser., S2.

Komazawa, M., K. Nakamura, J. Akamatsu, L. Jiang, K. Li, K. Nishimura, H. Morikawa, T. Yano, K. Sakai, S. Utagawa, and D. Yang (2005): Gravity Basement Structure of Lijiang Basin and Hochin Basin in Yunnan Province, China, A Report of Research on Conjugate Faults and Basement

Structure of Lijiang Basin in Yunnan Province, China for the Purpose of Microzoning the Area, supported by a Grant in Aid for Scientific Research of the Ministry of Education and Science, Japan, 10-26.

Konishi, Y., Y. Fukuda, and Y. Nogi (2006): Surface ship gravity data obtained on board the icebreaker Shirase, Antarctic Record, **50**, 251-262. (in Japanese with English Abstract)

Kudo, T., A. Yamamoto, T. Nohara, H. Kinoshita, and R. Shichi (2004): Variations of gravity anomaly roughness in Chugoku district, Japan: Relationship with distributions of topographic linearments, Earth Planets Space, **56**, e5-e8.

Kuroishi, Y. (2001): A new geoid model for Japan, JGEOID2000, in Sideris (ed.), IAG Symposia **123**, Gravity, Geoid and Geodynamics 2000, Springer, 329-333.

Kuroishi, Y. (2003): Reference frames in space geodesy era – Part 1: Gravity and height, J. Geogr. Surv. Inst., **102**, 21-32. (in Japanese)

Kuroishi, Y. (2004): Quality of recent static gravimetric geoid models in and around Japan, Proc. Symp. on Precise Satellite Positioning: Breakthrough for Geodynamics study by Dedicated Satellite Gravity Missions, Earthq. Res. Inst., Univ. Tokyo, 129-138. (in Japanese)

Kuroishi, Y. and H. Denker (2003): On the handling of ship and altimetric gravity data and the effect on local gravimetric geoid models – an investigation around Japan, Les Cahiers de l’ECGS, **20**, 123-130.

Kuroishi, Y. and W. Keller (2005): Wavelet approach to improvement of gravity field-geoid modeling for Japan, J. Geophys. Res., **110**, B03402, doi:10.1029/2004JB003371, (15pp).

Kuroishi, Y. and H. Munekane (2005): Recovery of global gravity field from CHAMP precise science orbit data – Preliminary results, Proc. Symp. on Dedicated Satellite Gravity Missions observing flow in the Earth system, Earthq. Res. Inst., Univ. Tokyo, 126-135. (in Japanese with English abstract)

Kuroishi, Y, H. Ando, and Y Fukuda (2002): A new hybrid geoid model for Japan, GSIGEO2000. J. Geod., **76**, 428-436, Springer.

Kuroishi, Y., Y. Hiyama, K. Morita, and M. Watanabe (2004): Improved modeling of the gravimetric geoid model for Yakushima Island. 102nd Meeting Geod. Soc. Japan Program and Abstracts, 23-24, Geod. Soc. Japan and Coll. Land, Infrastructure and Transport.

Kuroishi, Y., D. D. Rowlands, and F. G. R. Lemoine (2005): Preliminary results of regional gravity field modeling from GRACE data in the vicinity of Japan, Prog. and Abst. Book, Dynamic Planet 2005, August 22-26, 2005, Cairns, Australia, 276.

Kuroishi, Y., D. D. Rowlands, and F. G. R. Lemoine (2006a): Regional gravity field modeling from GRACE data – test case for the vicinity of Japan, Geophys. Res. Abst. 8, 2006, European Geosciences Union, EGU06-A-03688.

Kuroishi, Y., D. D. Rowlands, and F. G. R. Lemoine (2006b): Regional gravity field modeling from

GRACE data for improvement of geoid modeling for Japan, EOS Trans, AGU 87 (36), Western Pac. Geophys. Meet. Suppl. Abst., G31A-05.

Kusumoto, S., M. Kinugasa, T. Abe, K. Nemoto, and S. Takemoto (2004): Microgravity survey across the estuary of the Fujikawa River (Fujikawa Fault System), Shizuoka, Japan, J. School Mar. Sci. Technol., **2**, 55-61.

Larsen, C.F., R. J. Motyka, J. T. Freymueller, K. A. Echelmeyer, and E. R. Ivins (2005): Rapid viscoelastic uplift in southeast Alaska caused by post-Little Ice Age glacial retreat, Earth Planet. Sci. Lett., **237**, 548– 560.

Matsumoto, G., S. Miyashita, S. Arai, T. Morishita, J. Maeda, H. Kumagai, Y. Ohtomo, and H. Dick (2003): Magmatism and "Crust-mantle boundary" on the ultra-slow spreading ridge as observed in Atlantis Bank, Southwest Indian ridge, J. Geogr., **112**, No. 5, 705-719.

Matsumoto, K., T. Sato, H. Fujimoto, Y. Tamura, M. Nishino, R. Hino, T. Higashi, and T. Kanazawa (2006): Ocean bottom pressure observation off Sanriku and comparison with ocean tide models, altimetry, and barotropic signals from ocean models, Geophys. Res. Lett., **33**, L16602, doi:10.1029/2006GL026706.

Miyamachi, H., S. Nakano, S. Hirano, and K. Goto (2004): Spatial relation between the aftershock distribution of the 1997 Northwestern Kagoshima Earthquakes and gravity anomalies in the aftershock region, Zisin 2, **56**, 383-386.

Miyamachi, H., D. Fujita, A. Yamamoto, S. Hirano, H. Yakiwara, K. Goto, S. Nakao, and T. Kakuta (2006): Gravity measurement in Amami-Oshima Island, Kagoshima, Japan, Geophys. Bull. Hokkaido Univ., **69**, 51-67.

Mjelde, R., I. Eckhoff, Solbakkenk, S. Kodaira, H. Shimamura, K. Gunnarsson, A. Nakanishi, and H. Shiobara (2007): Gravity and S-wave modeling across the Jan Mayen Ridge, North Atlantic; implications for crustal lithology, Mar. Geophys. Res., **28**, No.1, 27-41.

Nawa, K. (2006): First observation of tsunami and T-phase using seismometers and a superconducting gravimeter at Syowa Station, Chikyu Monthly, **28**, 632-636. (in Japanese)

Nawa, K. and N. Suda (2003): Influence of sea level variations in seismic normal mode band at Syowa Station, Chikyu Monthly, **25**, 440-444. (in Japanese)

Nawa, K., N. Suda, S. Aoki, K. Shibuya, T. Sato, and Y. Fukao (2003): Sea level variation in seismic normal mode band observed with on-ice GPS and on-land SG at Syowa Station, Antarctica, Geophys. Res. Lett., **30**, 1402.

Nawa, K., Y. Murata, M. Komazawa, R. Morijiri, T. Hiroshima, M. Makino, F. Murakami, K. Kishimoto, S. Okuma, and R. Shichi (2005): Bouguer gravity anomalies in the Miyazaki district, Bull. Geol. Surv. Japan, **56**, 5/6, 183-208. (in Japanese)

Nawa, K., N. Suda, K. Doi, K. Shibuya, T. Sato, and K. Satake (2006a): An analysis of sea level and gravity variations after the 2004 Sumatra earthquake observed at Syowa Station, Antarctica, Advances in Geosciences, 11-16.

Nawa, K., K. Satake, N. Suda, K. Doi, K. Shibuya, and T. Sato (2006b): Sea level and gravity variation after the 2004 Sumatra Earthquake observed at Syowa Station, Antarctica, in P. Tregonign and C. Rizos (eds.), IAG Symposia **130**, Dynamic Planet, Springer, 536-540.

Nishijima J., Y. Fujimitsu, S. Ehara, E. Kouno, and M. Yamauchi (2005a): Micro-Gravity Monitoring and Repeated GPS Survey at Hatchobaru Geothermal Field, Central Kyushu, Japan, Proc. World Geothermal Congress 2005, CD-ROM.

Nishijima J., Y. Fujimitsu, K. Fukuoka, and S. Ehara (2005b): Earthquake off Western Part of Fukuoka Prefecture on March 20, 2005 and High Density Gravity Anomaly Map, NEWS of WESTERN JAPAN NDIC, **33**, 19-22 . (in Japanese)

Nishijima, J., T. Hirano, and Y. Fujimitsu (2005c): Densed Gravity Survey around Kego Fault, Fukuoka City, Geothermal Volcanolog. Res. Rep. Kyushu Univ., **14**, 41-50. (in Japanese)

Nishizaka, N., H. Ohno, A. Asano, and J. Segawa (2006): Gravity measurement using a helicopter-mounted gravimeter in Iyo-Nada Sea and the surroundings northwest of Shikoku, Japan, Electric Power Civil Engineering, **321**, 122-126. (in Japanese).

Nomura, K., M. Watanabe, S. Okamura, and K. Morita (2006a): The Revision of Ellipsoidal height of GEONET sites and Hybrid Geoid Model, GSIGEO2000, J. Geogr. Surv. Inst., submitted. (in Japanese)

Nomura, K., M. Watanabe, T. Kikkawa, and K. Morita (2006b): Development of Hybrid Geoid Model around YAKUSIMA in Japan, J. Geogr. Surv. Inst., submitted. (in Japanese)

Nozaki, K. (2006): The generalized Bouguer anomaly, Earth Planets Space, **58**, 287 - 303.

Nozaki, K., S. Mitsuishi, and M. Sano (2005): Detection of cavities within breakwaters using a method of the synchronized microgravity survey, OYO Tech. Rep., **25**, 21-33. (in Japanese with English abstract)

Okubo S. (2005): Gravity changes associated with volcanism – observation, theory, and analysis, Kazan, Special Issue for the 50-th Anniversary, S49-S58. (in Japanese)

Okubo S., H. Oshima, J. Koyama, I. Kimura, F. Suga, Y. Hiyama, T. Maekawa, A. Takamori, and T. Shimoyama (2005a): Hybrid gravity measurement during the 2003 Tokachi-oki earthquake (M8.0), Chikyu Monthly, Special Issue **49**, 112-117. (in Japanese)

Okubo, S., A. Takagi, A. Araya, S. Matsumoto, K. Fukui, and W. Sun (2005b): An absolute gravimeter climbs to the top of Mt. Fuji, Chikyu Monthly, Special Issue 48, 56-61. (in Japanese)

Onodera, K., T. Kato, and N. Seo (2003): Crustal structure in the vicinities of Fukutoku-okanoba submarine volcano estimated from gravity and magnetic anomalies, Rep. Hydrogr. Oceanogr. Res., **39**, 23-31. (in Japanese with English abstract)

Rosat, S., T. Sato, Y. Imanishi, J. Hinderer, Y. Tamura, H. McQueen, and M. Ohashi (2005): High-resolution analysis of the gravest seismic normal modes after the 2004 Mw = 9 Sumatra earthquake using superconducting gravimeter data, Geophys. Res. Lett., **32**(13), CiteID L13304.

Saibi, H., J. Nishijima, and S. Ehara (2005): Joint Use of Analytic Signal, Second Vertical Derivative and Transformation Filter for 2D and 3D Gravity Data Interpretation, Proc. 3rd Int. Workshop on Earth Sci. Technol., 97-104.

Saibi, H., J. Nishijima, E. Aboud, and S. Ehara (2006a): Euler Deconvolution of Gravity Data in Geothermal Reconnaissance; the Obama Geothermal area, Japan, Butsuri-Tansa (Geophys. Exploration), **59**, 275-282.

Saibi, H., J. Nishijima, and S. Ehara (2006b): Processing and Interpretation of Gravity Data for the Shimabara Peninsula Area, Southwestern Japan, Mem. Fac. Engineering, Kyushu Univ., **66**, 129-146.

Saibi, H., J. Nishijima, S. Ehara, and E. Aboud (2006c): Integrated Gradient Interpretation Techniques for 2D and 3D Gravity Data Interpretation, Earth Planets Space, **58**, 815-821.

Saito, H., K. Tagomori, M. Honda, J. Kasagi, Y. Fujise, and S. Ehara (2006): Estimation of Fault Structure Using Densed Gravity Survey Data at Fukuoka City, J. Geothermal Resources Soc. Japan, **28**, 181-197.

Sasagawa, G., M. A. Zumberge, and M. Stevenson (1989): The 1987 Southeastern Alaska Gravity Calibration Range - Absolute and Relative Gravity Measurements, J. Geophys. Res., **94**, 7661-7666.

Sasahara, N. (2005a): A calculation of geoid height and gravity anomaly by using global gravity models, Tech. Bull. Hydrogr. Oceanogr., **23**, 78-82. (in Japanese)

Sasahara, N. (2005b): Comparison of marine gravity datum derived with satellite altimeter in the Japanese waters, Tech. Bull. Hydrogr. Oceanogr., **23**, 83-88. (in Japanese)

Sasahara, N., T. Yabuki, and T. Yanuma (2006a): Determination of marine geoid model around Japan, Rep. Hydrogr. Oceanogr. Res., **42**, 39-47. (in Japanese with English abstract)

Sasahara, N., K. Shiohara, and T. Yabuki (2006b): Accuracy evaluation and error compensation on the sea gravity data, Tech. Bull. Hydrogr. Oceanogr., **24**, 89-93. (in Japanese)

Sato, T., Y. Tamura, K. Matsumoto, Y. Imanishi, and H. McQueen (2004): Parameters of the fluid core resonance inferred from superconducting gravimeter data, J. Geodynamics, **38**, 375-389.

Sato, T., J. Okuno, J. Hinderer, D.S. MacMillan, H.-P. Plag, O. Francis, R. Falk, and Y. Fukuda (2006a): A geophysical interpretation of the secular displacement and gravity rates observed at Ny-Alesund, Svalbard in the Arctic - Effects of post-glacial rebound and present-day ice melting, Geophysical. J. Int., **165**, 729-743.

Sato, T., J.P. Boy, Y. Tamura, K. Matsumoto, K. Asari, H.P. Plag, and O. Francis (2006b): Gravity tide and seasonal gravity variation at Ny-Alesund, Svalbard in Arctic, J. Geodynamics, **41**, 231-241.

Sato, T., S. Miura, W. Sun, A. M. Kaufman, R. Cross, J. T. Freymueller, and M. Heavner (2006c):

ISEA (International geodetic project in SouthEastern Alaska) for rapid uplifting caused by glacial retreat: (4) Gravity tide observation, EOS Trans. AGU, **87**(52), Fall Meet. Suppl., Abstract G33B-0067.

Satomura, M., M. Watanabe, S. Okubo, S. Kusumoto, and S. Ueki (2005): Precise relative gravity measurements over Mt. Fuji, Geosci. Rep., Shizuoka Univ., **32**, 25-30. (in Japanese)

Segawa, J., E.J. Joseph, S. Kusumoto, T. Ishihara, E. Nakayama, and M. Satomura (2003): Development of the helicopter-mounted gravimeter and the study of the active faults running across the coastal lines over the continental shelves. In I. N. Tziavos (ed.), Gravity and Geoid 2002, 3rd Meeting of the International Gravity and Geoid Commission, ZITI, 30-33.

Segawa, J., E.J. Joseph, E. Nakayama, K.V. Kumar, S. Kusumoto, T. Ito, S. Sekizaki, T. Ishihara, and M. Komazawa (2005a): Application of gravimetry by helicopter to identify marine active faults and improve accuracy of geoid at coastal zones, in F. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 229-235.

Segawa, J., M. Komazawa, K.V. Kumar, E. Nakayama, E.J. Joseph, S. Kusumoto, K. Onodera, and Y. Kuroishi (2005b): Examination of consistency of marine gravity with land gravity in and around the Japanese islands using a helicopter-borne gravimeter, Earth Planets Space, **57**, 243-252.

Shichi, R., A. Yamamoto, T. Kudo, Y. Murata, K. Nawa, M. Komazawa, M. Nakada, H. Miyamachi, H. Komuro, Y. Fukuda, T. Higashi, Y. Yusa, I. Nakagawa, H. Watanabe, J. Oikawa, S. Kobayashi, and I. Ohno (2005): A Gravity Database of Southwest Japan: Application to Bouguer Gravity Imaging in Kyushu District, Southwest Japan, in F. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 236-241.

Sugano, T. (2006): Line-of-sight acceleration data analysis extended to GRACE gravity field recovery, AGU Fall Meeting, San Francisco, abstract #G13A-0027, December 2006.

Sugano, T. and K. Heki (2004a): High Resolution Lunar Gravity Anomaly Map from the Lunar Prospector Line-of-Sight Acceleration Data, Earth, Planets Space, **56**, 81-86.

Sugano, T. and K. Heki (2004b): Isostasy of the Moon from high-resolution gravity and topography data: Implication for its thermal history, Geophys. Res. Lett., **31**, L24703, doi:10.1029/2004GL022059.

Sugano, T. and K. Heki (2004c): Lunar interior studies using the Lunar Prospector line-of-sight acceleration data, Lunar and Planet. Sci. Conf., Houston, abstract no.1567, March 2004.

Sugano, T. and K. Heki (2005): High Resolution Lunar Gravity Anomaly Maps, Ann. Rep. Nat. Astron. Observatory Japan, **6**, 28.

Sugihara, M., T. Ishido, and T. Horikoshi (2006): Short-term microgravity changes due to shut-in of production and reinjection wells, the Ogiri geothermal field, Japan, GRC Trans., **30**, 965-970.

Sun, W. (2003): Asymptotic theory for calculating deformations caused by dislocations buried in a spherical earth – geoid change, J. Geod., **77**, 381-387.

Sun, W. (2004a): Discretization schemes in downward continuation of gravity, J. Geod. Geodynamics, **24**, 9-18.

Sun, W. (2004b): Short note: asymptotic theory for calculating deformations caused by dislocations buried in a spherical Earth – gravity change, J. Geod., **78**, 76-81, doi 10.1007/s00190-004-0384-3.

Sun W. and S. Okubo (2004a): Truncated co-seismic geoid and gravity changes in the domain of spherical harmonic degree, Earth Planets Space, **56**, 9, 881-892.

Sun W. and S. Okubo (2004b): Coseismic deformations detectable by satellite gravity missions: A case study of Alaska (1964, 2002) and Hokkaido (2003) earthquakes in the spectral domain, J. Geophys. Res., **109**, B04405, doi:10.1029/2003JB02554.

Sun, W. and S. Okubo (2005): Methods to study co-seismic deformations detectable by satellite gravity mission GRACE, in C. Jekeli et al. (eds.), IAG Symposia **129**, Gravity, Geoid and Space Missions, 346-351, Springer.

Sun, W., S. Miura, T. Sato, A. M. Kaufman, R. Cross, J. T. Freymueller, and A. Schiel (2006a): ISEA (International geodetic project in SouthEastern Alaska) for rapid uplifting caused by glacial retreat: (3) Absolute gravity measurements, EOS Trans. AGU, **87**(52), Fall Meet. Suppl., Abstract G33B-0062.

Sun, W., S. Okubo, and T. Sugano (2006b): Determining dislocation Love numbers using satellite gravity mission observations, Earth Planets Space, **58**, 497-503.

Suryantini, J. Nishijima, S. Ehara, and A. Susilo (2006): Gravity Study of Jatibarang Sub-basin and Surrounding Area; Implication to Heat Flow Map of Onshore North West Java Basin, Indonesia, Proc. 4th Int. Workshop on Earth Sci. Technol., 321-328.

Takemoto, S. and H. P. Sun (2004): Japan-China collaboration project on precise gravity measurements in East Asia, Progress in Geodesy and Geodynamics, (ISBN7-5352-3194-2/P 10), Hubei Science & Technology Press, 138-144.

Takemoto, S., Y. Fukuda, T. Higashi, M. Abe, S. Ogasawara, S. Dwipa, D. S. Kusuma, and A. Andan (2002): Effect of groundwater changes on SG observations in Kyoto and Bandung, Marees Terrestres Bulletin D'Informations, **136**, 10839-10848.

Takemoto, S., Y. Fukuda, T. Higashi, I. Kimura, Y. Hiraoka, Y. Hiyama, H. Nakagawa, M. Honda, T. Tanaka, H. Aoki, M. Hashizume, H. Amemiya, A. Suzuki, H. -P. Sun, Y. Wang, H. Xu, Y. Zhu, W. Zhang, J. F. Huang, T. K. Yeh, H. C. Yu, C. Hwang, S. Dwipa, D. S. Kusuma, P. Manurung, T. C. Hua, M. Yosof, S. Hj. Tahir, K. Wattananikorn, R. M. Agaton, and E. Macaspac (2006a): Establishment of an Absolute Gravity Network in East- and Southeast- Asia, J. Geod. Soc. Japan, **52**, 51-95. (in Japanese with English Abstract)

Takemoto, S., Y. Fukuda, T. Higashi, I. Kimura, Y. Hiraoka, H. -P. Sun, Y. Wang, H. Xu, J. F. Huang, P. Manurung, M. Yosof, B. A. Bakar, S. H. Tahir, and K. Wattananikorn (2006b): Geodetic Monitoring of Gravity Changes in East- and Southeast-Asia Using Absolute Gravimeters, Proc.

2nd Southeast Asian Natural Resources and Environmental Management Conference, November 21-23, 2006, Kota Kinabalu, Sabah, Malaysia, 322-327.

Tamura, M., S. Ohtsu, T. Oka, S. Ishimaru, J. Okada, and A. Yamamoto (2003): Gravity Survey around the Area of Furano Active zone, Central Hokkaido Area, Abstracts Japan Earth Planet. Sci. Joint Meeting, D005-P001.

Tamura, Y., T. Sato, Y. Fukuda, and T. Higashi (2005): Scale Factor Calibration of a Superconducting Gravimeter at Esashi Station, Japan using Absolute Gravity Measurements, J. Geodesy, **78**, 481-488.

Tanaka, K., M. Mishina, J. Inoue, T. Hasegawa, T. Honda, T. Takayama, T. Sato, and T. Nomura (2006): Gravity anomalies of active volcanoes in northeastern Japan, Bull. Fac. Sci. Tech. Hirosaki Univ., **8**, 7-24. (in Japanese)

Tanaka, Y., J. Okuno, and S. Okubo (2006): A new method for the computation of global viscoelastic post-seismic deformation in a realistic earth model (I)—vertical displacement and gravity variation, Geophys. J. Int., **164**, 2, 273-289.

Tanaka, T., H. Aoki, A. J. Martin, K. Oshita, K. Nozaki, and M. Onishi (2004): Subsurface structure under a basaltic monogenetic volcano near the active Atera fault, Tectonophysics, **378**, 197-208.

Tanaka, T., H. Aoki, K. Oshita, and K. Nozaki (2005): Microgravity survey in the southern tip of the Atera fault, central Japan, in F. Sanso (ed.), IAG Symposia**128**, A Window on the Future of Geodesy, Springer, 567-570.

Tanaka, T., W. Salden, A. J. Martin, H. Saegusa, Y. Asai, Y. Fujita, and H. Aoki (2006): Variations of absolute gravity accompanying earthquake-induced changes in subsurface pore water pressure at the Mizunami Underground Research Institute construction site, central Japan, Geochem. Geophys. Geosys., **7**, 3, Q03017.

Tsuji, H., Y. Shirai, M. Ohtaki, K. Sugihara, R. Kawamoto, K. Takashima, I. Kimura, and T. Inoue (2004): Response of the Geodetic Department of GSI to the Tokachi-oki Earthquake in 2003, J. Geogr. Surv. Inst., **105**, 3-10. (in Japanese)

Ueda, Y. (2003): Gravity terrain correction by automatic interpolation of basi topographic mesh data, J. Japan Soc. Mar. Surv. Tech., **15**(2), 17-27. (in Japanese with English abstract)

Ueda, Y. (2005): Bouguer gravity anomalies (ver. 2004) of Japanese island arcs and its adjacent seas, Rep. Hydrogr. Oceanogr. Res., **41**, 1-26. (in Japanese with English abstract)

Ueki, S., S. Okubo, H. Oshima, T. Maekawa, W. Sun, S. Matsumoto, and E. Koyama (2005): Gravity Change Preceding the 2004 Eruption of Asama Volcano, Central Japan, Kazan, **50**, 377-386. (in Japanese with English abstract)

Ukawa, M., E. Fujita, H. Ueda, K. Nozaki, and K. Iwamoto (2006): Gravity changes measured by Scintrex CG-3M gravimeters at Ogasawara Iwo-jima, J. Geod. Soc. Japan, **52**, 37-50. (in Japanese with English abstract)

Xu, P. L., Y. Fukuda, and Y. Liu (2006a): Multiple parameter regularization: Numerical solutions and applications to the determination of geopotential from precise COSMIC orbits, J. Geod., **80**, 17-27.
Xu, P. L., Y. Z. Shen, Y. Fukuda, and Y. Liu (2006b): Variance component estimation in linear inverse ill-posed models, J. Geod., **80**, 69-81.
Yamamoto, K., S. Okubo, M. Furuya, A. Araya, S. Matsumoto, T. Takayama, and K. Ishihara (2003): Absolute gravity measurements at Sakurajima volcano during the period 1998-2002, Disast. Prev. Res. Inst. Annals, Kyoto Univ., **46**(B), 827-833. (in Japanese)
Yamamoto, K., T. Otsubo, T. Kubo-oka, and Y. Fukuda (2005): A simulation study of effects of GRACE orbit decay on the gravity field recovery, Earth Planets Space, **57**, 291-295.

6. Crustal Deformation

Heki (2006) reviewed crustal deformation studies in Japan included in a book that summarizes review talks given in the 2003 Snowbird Meeting, USA. Sagiya (2004) reviewed variety of crustal deformation studies based on continuous GPS observation for 10 years.

Bibliography

Heki, K. (2006): Secular, transient and seasonal crustal movements in Japan from a dense GPS array: Implication for plate dynamics in convergent boundaries, in T. Dixon and C. Moore (eds.), The Seismogenic Zone of Subduction Thrust Faults, Columbia University Press.
Sagiya, T. (2004): A decade of GEONET: 1994-2003 - The continuous GPS observation in Japan and its impact on earthquake studies -, Earth Planets Space, **56**, xxix-xli.

6.1 Secular Movements

6.1.1 Plate Motion

Munekane and Fukuzaki (2006) made a precise plate motion model for tectonic plates surrounding Japan by giving the up-to-date GPS velocity fields in the framework of ITRF 2000. They concluded that the obtained plate motion parameters generally agreed well with those proposed by the previous studies. They also argued that the precisions of their parameters were improved by the abundance of the data used for their fitting.

Kato et al. (2003) first discovered the geodetic evidence of back arc spreading of Mariana Trough using GPS. Special attention was paid in their article that there was a slight arc parallel extension along the Mariana arc. Kato and Kubo (2006) discussed the arc parallel extension at four island arcs; Mariana, Southwestern Japan, Tonga and Hellenic, using GPS and stress orientation estimated by earthquake mechanisms. Watanabe and Tabei (2004) divided the Ryukyu arc region, southwest Japan into several crustal blocks and determined their motions based on GPS horizontal velocities on land and strain rates translated from seismic moment tensor data at the plate subduction zone and the back-arc opening zone.

Iwakuni et al. (2004) made GPS observation in Thailand and delineated the velocity field in the Indo-china Peninsula. Results suggest that the peninsula is mostly rigid and moves toward ESE, which is in parallel with the Sunda Plate motion. Kato (2003) reviewed the displacement rate field in East Asia and western Pacific based on GPS measurements.

6.1.2 Interseismic Motion

Japan is situated in an active plate boundary zone. So the observed crustal deformation reflects interseismic stress accumulation process at subduction zones and active faults. Numerous observational studies have been conducted in this context.

The Northeastern Japan arc is located in a typical subduction zone, and is a seismically active region where large interplate earthquakes have occurred repeatedly. Suwa et al. (2006) estimated three components of displacements at GEONET stations for the period from 1997 to 2001 to reveal WNW-ESE contraction together with subsidence along the Pacific Ocean coast. Using the 3-D site velocities as the data for a geodetic inversion analyses, a new model of interplate coupling is proposed to demonstrate two strongly coupled areas centered at around lat 38˚ N and 42˚ N along Japan and Kuril Trenches.

Earthquakes with magnitudes of about 7.5 have repeatedly occurred in the southern strongly coupled area, east off Miyagi Prefecture (Miyagi-oki) with an averaged interval of about 37 years. Based on historical records of these recurrent earthquakes, the Headquarters of Earthquake Research Promotion of Japan (HERP) stated that the next Miyagi-oki earthquake will occur with a probability of about 50 % in the next 10 years after 2003 (HERP, 2003). In response to this assessment, Tohoku University established 13 new continuous GPS stations around the source area of the 1978 event to complement GEONET.

Miura et al. (2004) derived a map of the strain rate distribution in NE Japan showing that there exists a notable strain concentration zone of EW contraction along the Volcanic Front. The area demonstrates active seismicity including some disastrous earthquakes. Recent seismic tomography studies have revealed the existence of inclined seismic low-velocity zones (LVZ) at depths shallower than about 150 km in the mantle wedge sub-parallel to the subducted slab. The inclined LVZ reaches the Moho right beneath the Volcanic Front, indicating that the formation of the strain concentration zone is closely related to the rheological structure of the island-arc system.

JHOD's seafloor geodetic observation has revealed an intraplate crustal movement of 7.3 cm/yr WNW relative to the stable part of Eurasian Continent at a seafloor reference station located off Miyagi Prefecture, landward of Japan Trench (Fujita et al., 2006a; 2006b).

Ohta et al. (2004) studied the interplate coupling based on continuous GPS data in Tokai District, central Japan, where a large earthquake has been anticipated since the 1970s. Their estimation of coupled region on the plate boundary is in good accordance with the hypothetical source model of the Tokai earthquake.

Tabei et al. (2003) carried out campaign-based dense GPS observations across the Median Tectonic Line (MTL), southwest Japan and decomposed crustal deformation filed into two different modes: interseismic crustal shortening in the direction of convergence of subducting Philippine Sea Plate and permanent lateral slip of the forearc block along MTL. Sagiya et al. (2004) studied crustal deformation around ITL, another major geologic structure in central Japan, by GPS measurement. Heterogeneous deformation along the fault line has become evident, which is consistent with geologically estimated fault types. But there are many unknown factors associated with deformation processes at the deep portion of the fault. Nishimura et al. (2004) analyzed the data of the dense GPS network across Nagamachi-Rifu Fault Zone, northeast Japan and found a high strain rate zone in the western part of the fault zone. Fujimori (2003) clarified that a creep fault extends from Akashi Strait to the north part of Chubu District through North Biwa Lake.

Murakami and Ozawa (2004) mapped spatial distribution of vertical displacement rate over Japan and discussed its implications. Among the results they argued the difference of depths of down dip tip of coupling region along subduction plate boundary between northeast and southwest Japan, where old and cold Pacific Plate and young and hot Philippine Sea Plate are subducting, respectively.

Kudo and Yamaoka (2003) discussed the driving force for the basin subsiding against isostatic balance in and around Lake Biwa in Kinki District, central Japan. The induced mantle flow due to the subduction of the Philippine Sea Slab and the pressure distribution on the crust-mantle boundary is simulated.

Iinuma et al. (2004) conducted GPS measurements in Costa Rica. They found velocity field along the profile perpendicular to the Pacific coast of the country. They analyzed the data and estimated the area of plate coupling where an earthquake is considered to be imminent.

Hot Spring Research Institute of Kanagawa Prefecture (HSRI) is monitoring crustal deformation by means of GPS, EDM, tilt, and ground water level in the western Kanagawa area near Odawara, where a M7 class earthquake has been anticipated (Daita et al., 2003a; 2003b; 2004; Harada et al., 2004; 2005; 2006; Honda et al., 2006; Itadera et al., 2003; 2004; Itadera and Ito, 2005; 2006; Tanbo et al., 2005; Tanada et al., 2004). They also tried numerical modeling of the Izu collision zone

(Tanbo and Tanada, 2003).

The Needles District in Canyonlands National Park, Utah, is located southeast of the confluence of Colorado and Green Rivers, and includes elongated, extensional fault blocks that have accommodated flexure of a thin sequence of sedimentary rock. Furuya et al. (2005) reported their observational results derived by applying both the standard InSAR analysis and the Interferometric Point Target Analysis (IPTA) similar to the Permanent Scatterer technique.

Chaman Fault System is an on-land transform separating Indian and Asian Plates. Szeliga et al. (2006) presented InSAR analyses that suggest that a 110-km segment of Chaman Fault System north of Quetta may be experiencing shallow aseismic slip (creep). ERS-1/-2 data indicate a change in range along the 110-km segment by as much as 7.8 mm/yr.

Bibliography

Daita, Y., T. Tanada, and H. Ito (2003a): Tilt observation in the western Kanagawa Prefecture (2002), Bull. Hot Springs Res. Inst. (Catfish Letters), **53**, 33-36.(in Japanease)

Daita, Y., T. Tanada, and H. Ito (2003b): GPS and EDM observations in the western Kanagawa Prefecture (2002), Bull. Hot Springs Res. Inst. (Catfish Letters), **53**, 37-42. (in Japanease)

Daita, Y., T. Tanada, H. Ito, and M. Harada (2004): Tilt observation in the western Kanagawa prefecture (2003), Bull. Hot Springs Res. Inst. (Catfish Letters), **54**, 7-10. (in Japanease)

Fujimori, K. (2003): Tectonics Revealed by GEONET Data in the Kinki District, Annuals Disast. Prev. Res. Inst. Kyoto Univ., No. 46B, 663-669. (in Japanese with English Abstract)

Fujita, M., T. Ishikawa, M. Mochizuki, M. Sato, S. Toyama, M. Katayama, Y. Matsumoto, T. Yabuki, A. Asada, and O. L. Colombo (2006a): GPS/Acoustic seafloor geodetic observation: method of data analysis and its application, Earth Planets Space, **58**, 265-275.

Fujita, M., Y. Matsumoto, T. Ishikawa, M. Mochizuki, M. Sato, S. Toyama, K. Kawai, T. Yabuki, A. Asada, and O. L. Colombo (2006b): Combined GPS/Acoustic seafloor geodetic observation system for monitoring off-shore active seismic regions near Japan, Proc. ION GNSS-2006, Fort Worth, Texas.

Furuya, M., K. Mueller, and J. Wahr (2005): Active salt tectonics in the Needles District, Canyonlands (Utah) detected by Interferometric SAR and Point Target Analysis: 1992-2002, EOS Trans. AGU, **86**(52), Fall Meet. Suppl., Abstract G51C-0854.

Harada, M., T. Tanada, T. Tanbo, and H. Ito (2004): GPS observation in the western Kanagawa prefecture (2003), Bull. Hot Springs Res. Inst. (Catfish Letters), **54**, 11-14.(in Japanease)

Harada, M., T. Tanada, H. Ito, and Y. Daita (2005): Tilt observation in the western Kanagawa prefecture (2004), Bull. Hot Springs Res. Inst. (Catfish Letters), **55**, 7-10. (in Japanease)

Harada, M., T. Tanada, H. Ito, and R. Honda (2006): GPS and EDM observation in the western Kanagawa prefecture (2005), Bull. Hot Springs Res. Inst. (Catfish Letters), **56**, 11-16.(in

Japanease)

Honda, R., T. Tanada, M. Harada, and H. Ito (2006): Tilt observation in the western Kanagawa prefecture (2005), Bull. Hot Springs Res. Inst. (Catfish Letters), **56**, 7-10.(in Japanease)

Itadera, K. and H. Ito (2005): Groundwater level changes in the western Kanagawa prefecture (2004), Bull. Hot Springs Res. Inst. (Catfish Letters), **55**, 19-22. (in Japanease)

Itadera, K. and H. Ito (2006): Groundwater level changes in the western Kanagawa prefecture (2005), Bull. Hot Springs Res. Inst. (Catfish Letters), **56**, 17-22. (in Japanease)

Itadera, K., Y. Daita, T. Tanada, and H. Ito (2003): Groundwater level changes in the western Kanagawa Prefecture (2002), Bull. Hot Springs Res. Inst. (Catfish Letters), **53**, 43-46. (in Japanease)

Itadera, K., Y. Daita, and T. Tanbo (2004): Groundwater level changes in the western Kanagawa prefecture (2003), Bull. Hot Springs Res. Inst. (Catfish Letters), **54**, 17-20. (in Japanease)

Iinuma, T., M. Protti, K. Obana, V. Gonzalez, R. Van der Laat, T. Kato, S. Miyazaki, Y. Kaneda, and E. Hernandez (2004): Inter-plate coupling in the Nicoya Peninsula, Costa Rica, as deduced from a trans-peninsula GPS experiment, Earth Planet. Sci. Lett., **223**, 203-212.

Ito, T. and M. Hashimoto (2004): Spatiotemporal distribution of Interplate coupling in southwest Japan from inversion of geodetic data, J. Geophys. Res., **109**, B02315, doi:10.1029/2002JB002358.

Iwakuni, M., T. Kato, H. Takiguchi, T. Nakaegawa, and M. Satomura (2004): Crustal deformation in Thailand and tectonics of Indochina peninsula as seen from GPS observations, Geophys. Res. Lett., **31**, L11612, doi:10.1029/2004GL020347

Kato, T. (2003): Tectonics of the eastern Asia and the western Pacific as seen by GPS observations, Geosci. J., **7** (1), 1-8.

Kato, T. and A. Kubo (2006): Present-day tectonics of four active island arcs based on GPS observations and forearc stress fields, in Back-arc spreading systems: geological, biological, chemical, and physical interactions, AGU Geophys. Monograph Ser. **166**, 193-204.

Kato, T., J. Beavan, T. Matsushima, Y. Kotake, J. T. Camacho, and S. Nakao (2003): Geodetic evidence of back-arc spreading in the Mariana Trough, Geophys. Res. Lett., **30**, 1625, doi: 10.1029/2002GL016757.

Kudo, T. and K. Yamaoka (2003): Pull-down basin in the central part of Japan due to subduction-induced mantle flow, Tectonophysics, **367**, Issues 3-4, 203-217.

Miura, S., T. Sato, A. Hasegawa, Y. Suwa, K. Tachibana, and S. Yui (2004): Strain concentration zone along the volcanic front derived by GPS observations in NE Japan arc, Earth Planets Space, **56**, 1347-1355.

Munekane, H. and Y. Fukuzaki (2006): A plate motion model around Japan, Bull. Geogr. Surv. Inst., **53**, 35-41.

Murakami, M. and S. Ozawa (2004): Mapped Vertical Deformation Field of Japan Derived from Continuous GPS Measurements and Its Tectonic Implications, Zisin 2, **57**, 209-231. (Japanese with English Abstract)

Nishimura, T., T. Sagiya, and S. Miura (2004): Crustal deformation around the Nagamachi-Rifu Fault zone and its vicinity (central Tohoku), Northeastern Japan, observed by a continuous GPS network, Zisin 2, **56**, 497-509. (in Japanese with English abstract)

Ohta Y., F. Kimata, and T.Sagiya (2004): Reexamination of the interplate coupling in the Tokai region, Central Japan, based on the GPS data in 1997-2002, Geophys. Res. Lett., **31**, doi:10.1029/2004GL021404.

Sagiya T., T. Nishimura, and Y. Iio (2004): Heterogeneous crustal deformation along the Central-Northern Itoigawa-Shizuoka Tectonic Line Fault System, central Japan, Earth Planets Space, **56**, 1247-1252.

Suwa, Y., S. Miura, A. Hasegawa, T. Sato, and K. Tachibana (2006): Interplate coupling beneath NE Japan inferred from three-dimensional displacement field, J. Geophys. Res., **111**, B04402, doi:10.1029/2004JB003203.

Szeliga, W. M., M. Furuya, S. Satyabala, and R. Bilham (2006): Surface Creep along the Chaman Fault on the Pakistan-Afghanistan Border imaged by SAR interferometry, EOS Trans. AGU, **87**(52), Fall Meet. Suppl., Abstract T43D-1661.

Tabei, T., M. Hashimoto, S. Miyazaki, and Y. Ohta (2003): Present-day deformation across the southwest Japan arc: Oblique subduction of the Philippine Sea plate and lateral slip of the Nankai forearc, Earth Planets Space, **55**, 643-647.

Tanada, T., Y. Daita, H. Ito, T. Tanbo, and M. Harada (2004): EDM observation in the western Kanagawa prefecture (2003), Bull. Hot Springs Res. Inst. (Catfish Letters), **54**, 15-16. (in Japanease)

Tanbo, T. and T. Tanada (2003): Contact analysis of the plate boundary in the western area of Kanagawa prefecture with the crustal movement analysis software ”CHIKAKU system¨, Bull. Hot Springs Res. Inst., **35**, 17-28. (in Japanease)

Tanbo, T., T. Tanada, M. Harada, and H. Ito (2005): GPS and EDM observation in the western Kanagawa prefecture (2004), Bull. Hot Springs Res. Inst. (Catfish Letters), **55**, 11-18. (in Japanease)

Watanabe, T. and T. Tabei (2004): GPS velocity field and seismotectonics of the Ryukyu arc, southwest Japan, Zisin 2, **57**, 1-10. (in Japanese)

6.2 Transient Movements

6.2.1 Coseismic Movements

Using geodetic data GSI has been routinely making fault models immediately after medium and major sized earthquakes occurring around Japan. In recent cases, the most powerful data have been provided by the temporally continuous crustal deformation results obtained from GEONET distributed over Japan. For example, Imakiire (2004), Nishimura et al. (2003) together with Nishimura et al. (2004) and Nishimura et al. (2005), Nishimura et al. (2006) and Imakiire and Nishimura (2006) summarized fault models for the 2003 Tokachi-oki Eq. M8.0, 2003 Northern Miyagi Eq. M6.2, Fukuokaken Seiho-oki Eq. 7.0 and 2004 Mid Niigata Prefecture Eq. M6.8, respectively.

GSI makes fault models also for major earthquakes outside Japan using remote sensing data. Analyses of satellite radar imagery before and after the 2004 and 2005 Sumatra earthquakes by Tobita et al. (2006) revealed the uplift and submergence distributions over the islands along the subduction zone. They outlined the regions that experienced coseismic vertical deformation.

National Research Institute for Earth Science and Disaster Prevention (NIED) carried out detection of crustal deformations associated with earthquakes using InSAR technique. Ozawa et al. (2005) applied RADARSAT InSAR and detected coseismic and postseismic deformations related to the Mid Niigata Prefecture earthquake that occurred on 23 October 2004. Ozawa et al. (2006) applied ENVISAT InSAR and detected coseismic deformation associated with the Fukuokaken Seiho-oki earthquake that occurred on 20 March 2005.

An image matching technique at subpixel level was applied to SAR images of northern Pakistan for the mapping of displacement field (Tobita, 2006). The obtained distribution of 3-D displacement vectors illustrated the detailed pattern of deformation field associated with the M7.6 Northern Pakistan earthquake of 8 October 2005. The map demonstrated that the earthquake occurred along pre-existing active faults.

A great earthquake with M8.0 (the 2003 Tokachi-oki earthquake) occurred on 26 September 2003, in the latter area. Miura et al. (2004) estimated the coseismic slip-distribution using GPS data to obtain consistent results with that inferred from waveform inversions. The maximum coseismic slip roughly accounts for the slip-deficit accumulated in the past 51 years, assuming that the back-slip rate has been nearly constant since 1952, when the 1952 M8.2 Tokachi-oki earthquake occurred at about the same epicenter.

The 2003 Tokachi-oki earthquake (Mj8.0) is a large inter-plate earthquake. The strain seismograms caused by the earthquake were successfully recorded by Ishii-type borehole strainmeters array and quartz-tube extensometers about 1000 km away from the epicenter. Okubo et al. (2004) compared with the strain seismograms recorded by the Ishii-type borehole strainmeters, quartz-tube extensometers, and broadband seismograms at the range of frequency of seismic waves (0.001-1 Hz). The following results were obtained: the Ishii-type borehole instruments have good responses as well as quartz-tube extensometers, Ishii-type borehole strainmeters are more sensitive than broadband seismometers in very low frequency range (f < 0.003 Hz).

The 2004 off the Kii Peninsula earthquakes (Mj7.1 and Mj7.4) occurred at Nankai Trough, on 5 September 2004. Clear strain-steps associated with these earthquakes were observed with Ishii-type borehole strainmeters and quartz-tube extensometers in Tokai and Kinki Districts. Asai et al. (2005) investigated the spatial and depth distribution of the observed principal strain changes and compared the observed strain-steps and theoretical calculations at all observatories. The following results were obtained: the observed strain-steps at all observatories are generally consistent with the polarities of the theoretical values, and the observed strain-step increases with depth at the same place. At the Togari site, the following relationships are obtained: the strain-step and the tidal strains increase with depth and increasing of the modulus of elasticity, namely, hardness of rock. Asai et al. (2005) consider that the geological structure around the observatory may cause a modification of the strain field. Okubo et al. (2005) also investigated the dynamic strain variations caused by the 2004 off the Kii Peninsula earthquakes (Mj7.1 and Mj7.4), and clarified the relation between dynamic strain and velocity. Their results will contribute greatly to seismology. Okubo et al. (2005) also clarified the strain-step formation process. This result and the concept of dynamic strain will bring more information to geodetics.

A large earthquake with M7.2 occurred on 16 August 2005 east off Miyagi Prefecture (the 2005 Miyagi-oki earthquake). Coseismic and postsesimic deformations associated with this event were investigated by Miura et al. (2006) to reveal the causal interplate slips using continuous GPS data and geodetic inversion. The coseismic slip distribution shows good agreement with that estimated by seismic waveform inversions. The major slip area is limited to the southeastern part of the rupture area of the previous 1978 event (M7.4). The postseismic slip extended to the southwest of the coseismic slip area. These distinctive features of both the coseismic and postseismic slips might be caused by the existence of the locked plate interface, where seismogenic stress has not released yet, in the northern part of the 1978 rupture area.

Shizuoka University carried out continuous laser ranging measurements at Shizuoka, central Japan, and discussed tectonics of the central Japan before and after the 2004 Mid Niigata Prefecture earthquake with their data (Niitsuma et al., 2005).

Sagiya (2003) studied coseismic displacement of the 1918 Omachi earthquake. He conducted an integrated analysis of coseismic signals contained in leveling and triangulation data with contemporary GPS data and structural information. In addition, investigation of original leveling record revealed an artificial error in the official dataset.

Bibliography

Asai, Y., M. Okubo, H. Ishii, H. Aoki, T. Yamauchi, Y. Kitagawa, and N. Koizumi (2005):

Co-seismic strain-steps associated with the 2004 off the Kii peninsula earthquakes-Observed with Ishii-type borehole strainmeters and quartz-tube extensometers, Earth Planets Space, **57**, 309-314.

Imakiire, T. (2004): A Fault Model and Postseismic Deformation of 2003 Tokachi Earthquake Derived from GEONET Measurements, Seismo, **8**, 1, 10-11.

Imakiire, T. and T. Nishimura (2006): Fault model of Chuetsu earthquake based on crustal deformation data, Chikyu Monthly, Special Issue, **53**, 76-18.

Miura, S., Y. Suwa, and A. Hasegawa (2004): The 2003 M8.0 Tokachi-Oki earthquake – How much has the great event paid back slip debts?, Geophys. Res. Lett., **31**, L05613, doi:10.1029/2003GL019021.

Miura, S., T. Iinuma, S. Yui, N. Uchida, T. Sato, K. Tachibana, and A. Hasegawa (2006): Co- and post-seismic slip associated with the 2005 Miyagi-oki earthquake (M7.2) as inferred from GPS data, Earth Planets Space, **58**(12), 1567-1572.

Niitsuma, N., S. Toma, H. Itoh, and T. Yashimoto (2005): The 2004 Chuetsu Earthquake in Niigata Prefecture and strain of the central Japan detected with laser ranging of the Crustal Activity Observatory of Shizuoka University, Geosci. Rep. Shizuoka Univ., **32**, 11-24. (in Japanese)

Nishimura, T., T. Imakiire, H. Yarai, T. Ozawa, M. Murakami, and M. Kaidzu (2003): A preliminary fault model of the 2003 July 26, M6.4 northern Miyagi earthquake, northeastern Japan, estimated from joint inversion of GPS, leveling, and InSAR data, Earth Planets Space, **55**, 751-757.

Nishimura, T., T. Imakiire, H. Yarai, Mk. Murakami, M. Kaidzu, and T. Ozawa (2004): Crustal Deformation and a Fault Model Associated with the Northern Miyagi Earthquake on July 26, 2003 - Results from Joint Analysis of Geodetic Data, J. Geogr. Surv. Inst., **104**, 101-107.

Nishimura, T., T. Ozawa, T. Imakiire, H. Yarai, Mk. Murakami, and M. Kaidzu (2005): A Fault Model Associated with the 2003 Northern Miyagi Earthquake estimated from GPS, Leveling, and InSAR data, Chikyu Monthly, **27**, 2, 110-115.

Nishimura, T., S. Fujiwara, M. Murakami, H. Suito, M. Tobita, and H. Yarai (2006): Fault model of the 2005 Fukuoka-ken Seiho-oki earthquake estimated from coseismic deformation observed by GPS and InSAR, Earth Planets Space, **58**, 51-56.

Okubo, M., H. Ishii, and T. Yamauchi (2004): The 2003 Tokachi-oki Earthquake, Observed by Borehole Strainmeter Array –Comparison with Broadband Seismogram–, Zisin 2, **57**, 105-113. (in Japanese with English abstract)

Okubo, M., Y. Asai, H. Aoki, and H. Ishii (2005): The seismological and geodetical roles of strain seismogram suggested from the 2004 off the Kii peninsula earthquakes, Earth Planets Space, **57**, 303-308.

Ozawa, T., S. Nishimura, Y. Wada, and H. Ohkura (2005): Coseismic deformation of the Mid Niigata prefecture Earthquake in 2004 detected by RADARSAT/InSAR, Earth Planets Space, **57**, 423-428.

Ozawa, T., S. Nishimura, and H. Ohkura (2006): Crustal deformation associated with the 2005 west off Fukuoka prefecture earthquake derived from ENVISAT/InSAR, Rep. Nat. Res. Inst. Earth Sci. Disast. Prev., **69**, 1-6.

Sagiya, T. (2003): A new fault model for the 1918 Omachi earthquake -leveling data revision and integrated interpretation of multi-disciplinary data-, Zisin 2, **56**, 199-211. (in Japanese with English abstract)

Suito, H., and S. Ozawa (2006): Crustal Deformation and Afterslip in Eastern Hokkaido since the Occurrence of 2004 Kushiro-Oki Earthquake, J. Geogr. Surv. Inst., **110**, 91-94. (in Japanese)

Tobita, M. (2006): Three-Dimensional Displacement Map of the 2005 Pakistan Earthquake Measured by SAR Image Offsets, Seismo, October 2006, 8-9. (in Japanese)

Tobita, M., H. Suito, T. Imakiire, M. Kato, S. Fujiwara, and M. Murakami (2006): Outline of vertical displacement of the 2004 and 2005 Sumatra earthquakes revealed by satellite radar imagery, Earth Planets Space, **58** (1), e1-e4.

6.2.2 Slow/Silent Deformation

Slow transient deformation occurring associated with plate subduction is attracting international attention in recent years. Understanding of such slow transients is crucially important in investigating physical processes at fault zones. GEONET has been playing a leading role in this research field.

GEONET detected several transient ground displacements associated with slow slip events and postseismic deformation. Transient motions were found in Tokai Region from late 2000 to 2005. The results of Ozawa et al. (2002; 2003b; 2003c; 2005) showed that interplate aseismic slip occurred in the western part of Tokai Region adjacent to the estimated source area of the next Tokai earthquake. The center of the Tokai slow slip was located beneath Lake Hamana. The estimated moment of the Tokai slow slip amounted to that of a M7.2 earthquake. Okada (2003) mentioned an interpretation about seismic activity in recent several years and abnormal crustal deformation in Tokai Region. Shimada and Kazakami (2005) summarized the time evolution of the slow event in the eastern part of this highly dynamic region through continuous GPS measurements. Miyazaki et al. (2006) investigated the 2000 Tokai slow slip event by applying the network inversion filter to continuous GPS data. The slip locus was found in the downdip extention of the locked zone where Tokai earthquake is anticipated. We then calculated the shear stress change. The rate dependence of the stress suggests a velocity weakening friction in the slow slip region.

Kobayashi and Yoshida (2004b) found that the long-term slow slip events in Tokai Region were occurred in the periods of 1980-1982 and 1988-1990 from tide gauge records at Maisaka. Kobayashi et al. (2006) investigated the data of the strainmeters of JMA and revealed at least more than 30 times strain changes associated with the short-term slow slip event since 1984.

Ozawa et al. (2004b) reported the slow slip events in the Bungo Channel area, southwest Japan. Their results showed the occurrence of aseismic interplate slips in the Bungo Channel area in 1997 and 2003. Although the both events occurred in a similar area with a similar magnitude (Mw7.1), the spatio-temporal evolution of the 2003 event was different from that of the 1997 event suggesting the difference in rupture processes. It took around one year for the both events to end. They argued that the Bungo Channel area releases strain energy accumulated by the subduction of Philippine Sea Plate through interplate aseismic slip processes at time intervals of around six years. Miyazaki et al. (2003) inverted continuous GPS time series with the network inversion filter to infer the space-time evolution of the 1996 Bungo slow thrust slip event and the afterslip following the 1996 Hyuga-Nada earthquake. The inversion suggests that those two events are independent in spite of a possibility of any causal relationship between them.

Similar slow slip events were found offshore of Boso Peninsula, central Japan, in 1996 and 2002 (Ozawa et al., 2003a). The two events occurred in a similar area with time duration of around ten days. In both cases, slip propagation from north to south was illustrated by spatio-temporal analysis. The Bungo slow slip event and the Boso slow slip event suggest existence of characteristic slow slip events at time intervals of around six years. Sagiya (2004a) conducted a detailed analysis of the 1996 Boso slow slip event comparing with the interseismic plate coupling in Kanto District. Based on the comparison, a general conclusion was obtained that seismic asperity and slow slip show compensating distribution each other.

Postseismic displacements were detected by GPS after many large earthquakes. Ozawa et al. (2004b; 2004c) reported that the postseismic slip occurred around the coseismic slip area of the 2003 Tokachi-oki earthquake M8.0. They also point out that the locations of the postseismic area and the coseismic slip area are complementary. Using continuous GPS data Murakami et al. (2006) revealed that a slow slip, which was triggered by the 2003 Tokachi-oki earthquake of M8, triggered two M7-class earthquakes off-Kushiro along Kuril Trench. This result implies a possibility of a realization of forecasting method of a certain type of earthquake. Time dependent inversion results by Suito and Ozawa (2006) showed that the postseismic slip in Off-Kushiro Region almost ended in middle of 2005, but still continues in Tokachi-oki Region.

Miyazaki et al. (2004) and Takahashi et al. (2004) analyzed GPS data after the 2003 Tokachi-oki earthquake (M8.0) and derived the postseismic crustal deformation due to the earthquake. Miyazaki et al. (2004) extended that the afterslip distributed around the main rupture region as the delayed response to the stress step. Their analysis also suggested that the rate dependence of the shear stress change is related to a velocity strengthening friction on the fault surface.

Sagiya et al. (2005) conducted continuous GPS observations shortly after the occurrence of the

2004 Mid-Niigata Prefecture earthquake. They detected significant postseismic movements, which can be interpreted as a result of fault afterslip.

Ohtani et al. (2003) and Kitagawa et al. (2006) indicated the possibility of an aseismic slip event at Yasutomi Fault from GPS, strain field and ground water pressure observations.

Nishimura et al. (2004) clarified temporal change of postseismic and interseismic velocity field of northeast Japan observed by GPS and estimated the annual change of interplate coupling on the subducting plate boundary. Their result shows transient from afterslip to the locking of the fault in the source area of the M7.7 1994 Sanriku-haruka-oki earthquake.

Yoshikawa (2003) calculated temporal and spatial variations of the strains caused by the slow slip event in Tokai Area from the GPS displacement data and evaluated influences on the anticipated Tokai earthquake. Kobayashi et al. (2003) found that crustal deformation in Chubu Region at and after the 2000 seismo-volcanic event around the northern Izu Islands. Kobayashi et al. (2005) interpreted that its deformation was caused by slow slip or a temporary suspension of the plate subduction in the focal region of the anticipated Tokai earthquake.

An important application of postseismic deformation study is the estimation of viscous property of the Earth’s lower crust and upper mantle. Ueda et al. (2003) observed postseismic crustal deformation following the 1993 Hokkaido Nansei-oki earthquake (M7.8), north Japan, by GPS, tide gauge and leveling measurements in southwest Hokkaido. By analyzing the three kinds of geodetic data comprehensively, they found that the dominant cause of the postseismic deformation is viscoelastic relaxation of the coseismic stress change in the uppermost mantle. Nishimura and Thatcher (2003) found the broad uplift following the 1959 Hebgen Lake earthquake in the western US was attributed to the visco-elastic relaxation in the uppermost mantle. They estimated that the visco-elastic structure consists of a 38-km-thick elastic plate over a visco-elastic half-space with viscosity of 4×10^{18} Pa s.

Postseismic transients can also be investigated with conventional survey data. Kobayashi and Yoshida (2004a) found that postseismic crustal deformation with two different relaxation times after the 1946 Nankai earthquake using tide gauge records. Nyst et al. (2006) re-evaluated the fault model of the 1923 Kanto earthquake using second order triangulation data as well as first order triangulation and leveling data. Pollitz et al. (2005) used the same dataset of Nyst et al. (2006) and found the location of asperities beneath Odawara and Miura Peninsula.

Ozawa et al. (2004d) detected postseismic deformation after the 1995 Hyogo-ken Nanbu earthquake by JERS-1 SAR interferometry.

Sagiya (2004b) revisit the conventional leveling survey data before the 1944 Tonankai earthquake. This dataset has been considered as a precursory change just prior to the megathrust event. But the detailed reanalysis raised several questions. The possibility of a precursory change cannot be denied but is severely re-questioned.

Bibliography

Kitagawa, Y., N. Koizumi, R. Ohtani, K. Watanabe, and S. Itaba (2006): Detection of aseismic slip on an inland fault by crustal movement and groundwater observations: A case study on the Yamasaki fault, Japan, PAGEOPH, **163**, 657-673.

Kobayashi, A. and A. Yoshida (2004a): Crustal deformation in and extended area after the 1946 Nankai earthquake deduced from tide gauge records, J. Geod. Soc. Japan, **50**, 39-42. (in Japanese)

Kobayashi, A. and A. Yoshida (2004b): Recurrence of the Tokai slow slip inferred from the tide gauge data at Maisaka, J. Geod. Soc. Japan, **50**, 209-212. (in Japanese)

Kobayashi, A., T. Yamamoto, H. Takayama, and A. Yoshida (2003): Crustal deformation in the Chubu-Kanto region at and after the 2000 seismic and volcanic activity around the northern Izu Islands, J. Geod. Soc. Japan, **49**, 121-133. (in Japanese)

Kobayashi, A., A. Yoshida, T. Yamamoto, and H. Takayama (2005): Slow slip in the focal region of the anticipated Tokai earthquake following the seismo-volcanic event in the northern Izu Islands in 2000, Earth Planets Space, **57**, 507-513.

Kobayashi, A., T. Yamamoto, K. Nakamura, and K. Kimura (2006): Short-term slow slip events detected by the strainmeters in Tokai region in the period from 1984 to 2005, Zisin 2, **59**, 19-27.

Miyazaki, S., J. J. McGuire, and P. Segall (2003): A transient subduction zone slip episode in southwest Japan observed by the nationwide GPS array, J. Geophys. Res., **108**, B2, 2087, doi:10.1029/2001JB000456.

Miyazaki, S., P. Segall, J. Fukuda, and T. Kato (2004): Space time distribution of afterslip following the 2003 Tokachi-oki earthquake: Implications for variations in fault zone frictional properties, Geophys. Res. Lett., **31**, L06623, doi:10.1029/2003GL019410.

Miyazaki, S., P. Segall, J. J. McGuire, T. Kato, and Y. Hatanaka (2006): Spatial and temporal evolution of stress and slip rate during the 2000 Tokai slow earthquake, J. Geophys. Res., **111**, B03409, doi:10.1029/2004JB003426.

Murakami, M., H. Suito, S. Ozawa, and M. Kaidzu (2006) : Earthquake Triggering by Migrating Slow Slip Initiated by M8 Earthquake along Kuril Trench, Japan, Geophys. Res. Lett., **33**, LO09306, doi:10.1029/2006GL025967.

Nishimura, T. and W. Thatcher (2003): Rheology of the lithosphere inferred from postseismic uplift following the 1959 Hebgen Lake earthquake, J. Geophys. Res., **108**, doi:10.1029/2002, JB002191. (erratum J. Geophys. Res., **109**, doi: 10.1029/2003JB002798)

Nishimura, T., T. Hirasawa, S. Miyazaki, T. Sagiya, T. Tada, S. Miura, and K. Tanaka (2004): Temporal change of interplate coupling in northeastern Japan during 1995-2002 estimated from continuous GPS observations, Geophys. J. Int., **157**, 901-916.

Nyst, M., T. Nishimura, F. F. Pollitz, and W. Thatcher (2006): The 1923 Kanto earthquake reevaluated using a newly augmented geodetic data, J. Geophys. Res., **111**, doi:10.1029/2005JB003628.

Ohtani R., Y. Kitagawa, N. Koizumi, and N. Matsumoto (2003): Verification of a non-secular change in a borehole strainmeter data using GPS: A case study of the Yasutomi station of the Geological Survey of Japan, AIST. Bull. Geol. Surv. Japan, **54**(5/6), 213 - 220.

Okada, Y. (2003): An interpretation to the anomalies on crustal activities in the Tokai region, Chikyu Monthly, suppl., **41**, 42-48. (in Japanese)

Ozawa, S., M. Murakami, M. Kaidzu, T. Tada, T. Sagiya, Y. Hatanaka, H. Yarai., and T. Nishimura (2002): Detection and monitoring of ongoing aseismic slip in the Tokai region, Central Japan, Science, **298**, 1009-1012.

Ozawa, S., S. Miyazaki, Y. Hatanaka, T. Imakiire, M. Kaidzu, and M. Murakmai (2003a): Characteristic silent earthquakes in the eastern part of the Boso peninsula, central Japan, Geophys. Res. Lett., **30**, 1283, doi:10.1029/2002GL016665.

Ozawa, S., M. Murakmai, M. Kaidzu, T. Tada, T. Sagiya, Y. Hatanaka, H. Yarai, and T. Nishimura (2003b): Monitoring of the ongoing Tokai slow slip, Chikyu Monthly, **25** (1), 70-74.

Ozawa, S., T. Sagiya, M. Murakmai, M. Kaidzu, Y. Hatanaka, and T. Imakiire (2003c): Current state of the Tokai slow slip and a possibility of coupling change between the Pacific plate and the Philippine Sea plate off shore of the Boso peninsula, Chikyu Monthly, **41**, 118-125.

Ozawa, S., Y. Hatanaka, M. Kaidzu, M. Murakami, T. Imakiire, and Y. Ishigaki (2004a): Aseismic slip and low-frequency earthquakes in the Bungo Channel, Southwestern Japan, Geophys. Res. Letters, **31**, L07609, doi:10.1029/2003GL019381.

Ozawa, S., M. Kaidzu, M. Murakami, T. Imakiire, and Y. Hatanaka (2004b): Coseismic and postseismic crustal deformation after the Mw8 Tokachi-oki earthquake in Japan, Earth Planets Space, **56**, 675-680.

Ozawa, S., M. Kaidzu, M. Murakami, T. Imakiire, and Y. Hatanaka (2004c): Crustal Deformation and interplate slip after the Tokachi-oki earthquake, Bull. Geogr. Surv. Inst., **105**, 11-15.

Ozawa, S., M. Murakami, M. Kaidzu, and Y. Hatanaka (2005): Transient crustal deformation in Tokai region, central Japan, until May 2004, Earth Planets Space, **57** (10), 909-915.

Ozawa, T., M. Tobita, H. Yarai, T. Nishimura, M. Murakami, and H. Ohkura (2004d): Postseismic deformation of the 1995 Hyogo-ken Nanbu earthquake revealed by JERS-1/InSAR, in C. Huang and Z. Qian (eds.), Proc. APSG Symp. Space geodesy and its applications to earth sciences, 105-111.

Pollitz, F. F., M. Nyst, T. Nishimura, and W. Thatcher (2005): Coseismic slip distribution of the 1923 Kanto earthquake, Japan, J. Geophys. Res., **110**, doi:10.1029/2005JB003638.

Sagiya, T. (2004a): Interplate coupling in the Kanto District, central Japan, and the Boso Silent earthquake in May 1996, PAGEOPH, **161**, 11-12, 2601-2616.

Sagiya, T. (2004b): Precursory crustal deformation of the 1944 Tonankai earthquake revisited, Chikyu Monthly, **26**, 746-753. (in Japanese)

Sagiya, T., M. Ohzono, S. Nishiwaki, Y. Ohta, T. Yamamuro, F. Kimata, and M. Sasaki (2005): Postseismic deformation following the 2004 Mid-Niigata Prefecture earthquake around the southern part of the source region, Zisin 2, **58**, 359-369. (in Japanese with English abstract)

Shimada, S. and T. Kazakami (2005): Time evolution of the eastern part of the ongoing Tokai slow event, Rep. Nat. Res. Inst. Earth Sci. Disast. Prev., **68**, 1-7.

Suito, H. and S. Ozawa (2006): Crustal Deformation and Afterslip in Eastern Hokkaido since the Occurrence of 2004 Kushiro-Oki Earthquake, J. Geogr. Surv. Inst., **110**, 91-94. (in Japanese)

Takahashi, H., S. Nakao, N. Okazaki, J. Koyama, T. Sagiya, T. Ito, F. Ohya, K. Sato, Y. Fujita, M. Hashimoto, Y. Hoso, T. Kato, T. Iinuma, J. Fukuda, T. Matsushima, Y. Kohno, and M. Kasahara (2004): GPS observation of the first month of postseismic crustal deformation associated with the 2003 Tokachi-oki earthquake (M_{JMA}8.0), off southeastern Hokkaido, Japan, Earth Planets Space, **56**, 377-382.

Ueda, H., M. Ohtake, and H. Sato (2003): Postseismic crustal deformation following the 1993 Hokkaido Nansei-oki earthquake, northern Japan: Evidence for a low-viscosity zone in the uppermost mantle, J. Geophys. Res., **108**, doi:10.1029/2002JB002067.

Yoshikawa, S. (2003): Space and time variation of strain promoted by the slow slip event in the Tokai area revealed by GPS data, Bull. Earthq. Res. Inst., Univ. Tokyo, **78**, 255-267. (in Japanese)

6.2.3 Volcanic Activities

During 2003-2006, volcanic activity in Japan was rather quiet. Small eruption occurred at Mt. Asama in September 2004. Sakura-jima becomes active in 2006, accompanied by a series of small eruptions. Mt. Meakan had a small eruption in February 2006. In other volcanoes, however, crustal deformation related to magma inflation or deflation continues. Geodetic measurements are conducted to monitor volcanic activities at a number of volcanoes on the Japan Islands by several institutions. NIED is operating the volcano observation networks in several Japanese volcanoes. GSI monitors volcanoes with their continuous GPS network. In addition, they repeated surveys of combination of campaign GPS measurements and leveling around 15 volcanoes of Japan.

Murakami (2005) made a model of magma supplying system beneath Asama Volcano, which erupted in 2004, combining the continuous GPS measurements and other data sets, such as, fumarole height, seismicity and emitted SO_2. He also pointed out that precursory inflation stage preceded by several months to the unrest stage, which sometimes then leads to an eruption. His results demonstrated an effectiveness of continuous GPS measurement for a practical eruption forecasting.

Oki et al. (2005) estimates volume of magma extruded inside of the summit crater of Asama Volcano during 2004 eruption using airborne SAR imagery and InSAR data.

Another inland volcano, Mt. Ontake has been monitored by repeated leveling. Kimata et al. (2004b) detected uplift around the seismic swarm area at the flank of Ontake. Later, volcanic activity was observed in late 2006 and dilatation was detected by continuous GPS measurements.

In 2000, there occurred volcanogenic seismic activity on a large scale in the Izu Islands, including the eruptions of Miyake-jima Island. It took around four months for the Izu Islands earthquakes to decline. GEONET detected transient deformation associated with the Izu Islands earthquakes. By using the crustal deformation data, Ozawa et al. (2004) estimated spatio-temporal evolution of a dike intrusion, creeping faults, and changes in pressure of magma chamber beneath Miyake-jima Island. The results show that magma intrusion occurred beneath Miyake-jima Island and migrated to Kozu-shima Island within several days. Yamaoka et al. (2005) reinvestigated the model for the 2000 dike intrusion event between Kozu-shima and Miyake-jima Volcano. The dike intrusion of large volume was detected by GEONET. The parameters in the dike intrusion models that reproduce the regional displacements due to the event are searched. Murase et al. (2006) analyzed GEONET data and their own GPS data on Kozu-shima, Nii-jima, and Miyake-jima to estimate a time-depnedent magma intrusion model for the 2000 event. In addition to the migrated magma from Miyake-jima, another direct intrusion from the deeper extension of the swarm area was estimated.

From continuous ground tilt and GPS observations, Ueda et al. (2005) showed that the 2000 eruptive activity of Miyake-jima Island had begun with an earthquake swarm and crustal deformation. Based on the crustal deformation data, they estimated the magma migration process at the initial stage (1830 LT on 26 June – 0600 LT on 27 June in 2000) of the activity. Irwan et al. (2003; 2006) also studied the initial stage of magma intrusion in the 2000 Miyake-jima eruption. Bando et al. (2005) studied the crustal deformation of Miyake-jima associated with the 14 July eruption. On the other hand, Furuya (2004) applied differential InSAR technique to Miyake-jima Island, south of Japan, and showed two localized significantly deforming areas with a magnitude of 4-6mm/yr in the radar line of sight by stacking radar interferograms between 1992 and 1998.

Izu-Oshima Volcano is a basaltic stratovolcano island on the northern edge of Philippine Sea Plate, about 100 km SSW of Tokyo, Japan. Recent eruptive activity extends back to November 1986. Furuya (2005) derived closed analytical solutions for a quasi-static thermoelastic deformation response to instantaneous point and spherical heat sources in an elastic half space, and then applied the solution to a radar interferometric observation of post-eruptive deformation associated with the 1986 fissure eruption at Izu-Oshima Volcano. Furuya (2006) apply Interferometric Point Target Analysis (IPTA) technique developed by Werner et al. (2003) to Izu-Oshima Volcano, using JERS SAR data from 1992 to 1998.

Another volcanic island, Hachijo-jima had a swarm activity in August 2002. Kimata et al. (2004a) detected a related dilatational change from GPS observation and estimated a dike intrusion model.

Okada et al. (2003) interpreted a seismic swarm east off Izu Peninsula, crustal deformation related to a volcanic activity, and so on.

HSRI monitors Hakone Volcano. They investigated tiltmeter record and sattelite data to detect crustal movement associate with a swarm activity in 2001 (Tanbo et al., 2005; Tanada and Watanabe, 2003).

The geodetic survey at Iwo-jima caldera, the average uplift rate of which is about 25 cm/yr over several hundred years, for more than 25 years revealed that the crustal deformation is characterized by two deformation modes: continuous contraction and episodic uplifts (Ukawa et al., 2005). Yarai et al. (2005) illustrated crustal deformation of Iwo-jima Volcano detected by repeated GPS observations.

Miyagi et al. (2004) analyzed crustal deformation of Okmok Volcano, Alaska, based on campaign mode GPS observation. Watanabe et al. (2005) proposed geodetic constraints for the mechanism of eruption of Anatahan Volcano, Northern Mariana Islands starting in May 2003. They determined co-eruptive displacement and transient movement during the activity at the sole GPS station on the island. Then they estimated locations and volume changes of the magma sources from the time series of the station coordinates.

Bibliography

Bando, N., S. Kariya, F. Kimata, S. Nakao, J. Oikawa, H. Watanabe, M. Ukawa, E. Fujita, K. Kawai, T. Matsushima, R. Miyajima, and T. Okuda (2005): Crustal deformation associated with the July 14, 2000 eruption of Miyakejima volcano detected by GPS measurements, Kazan, **50**, 173-182. (in Japanese with English abstract)

Furuya, M. (2004): Localized deformation at Miyakejima volcano based on JERS-1 radar interferometry: 1992-1998, Geophys. Res. Lett., **31**, L05605, doi:10.1029/2003GL019364.

Furuya, M. (2005): Quasi-static thermoelastic deformation in an elastic half space: theory and application to InSAR observations at Izu-Oshima volcano, Japan, Geophys. J. Int., **161**, 230-242.

Furuya, M. (2006): Application of JERS Interferometric Point Target Analysis to Izu-Oshima volcano, Japan, EOS Trans. AGU, **87**(52), Fall Meet. Suppl., Abstract G53D-0938.

Irwan, M., F. Kimata, N. Fujii, S. Nakao, H. Watanabe, S. Sakai, M. Ukawa, E. Fujita, and K. Kawai (2003): Rapid Deformation of Miyakejima Volcano on June 26-27, 2000 Detected by Kinematic GPS Analysis, Earth Planets Space, **55**, e13-e16.

Irwan, M., F. Kimata, and N. Fujii (2006): Time Dependent of Magma Intrusion Model During the Early Stage of The 2000 Miyakejima Activity, J. Volcanol. Geotherm. Res., **150**, 202-212.

Kimata, F., M. Irwan, and K. Fukano (2004a): Ground deformation at Hachijo Island, Japan on 13-22 August 2002 observed by GPS measurements and estimate dike intrusion model, Kazan, **49**, 13-22. (in Japanese with English abstract)

Kimata, F., R. Miyajima, M. Murase, D. Darwaman, T. Ito, Y. Ohata, M. Irwan, K. Takano, F. Ibrahim, E. Koyama, H. Tsuji, T. Takayama, K. Uchida, J. Okada, D. Solim, and H. Anderson (2004b): Ground Uplift Detected by Precise Leveling in the Ontake Earthquake Swarm Area, Central Japan in 2002-2004, Earth Planets Space, **12**, E45-E48.

Miyagi, Y., J.T. Freymueller, F. Kimata, T. Sato, and D. Mann (2004): Surface Deformation Caused by Shallow Magmatic Activity at Okmok Volcano, Alaska, Detected by GPS Campaigns 2000-2002, Earth Planets Space, **56**, E29-E32.

Murakami, M. (2005): Magma Plumbing System of the Asama Volcano Inferred from Continuous Measurements of GPS, Kazan, **50,** (5), 347-361. (Japanese with English Abstract)

Murase, M., M. Irwan, S. Kariya, T. Tabei, T. Okuda, R. Miyajima, J. Oikawa, H. Watanabe, T. Kato, S. Nakao, M. Ukawa, E. Fujita, M. Okayama, F. Kimata, and N. Fujii (2006): Time dependent model of magma intrusion in and around Miyake and Kozu islands, central Japan in June-August, 2000, J. Volcanol. Geotherm. Res., **150**, 213-231.

Okada Y., E. Yamamoto, Y. Okubo, and M. Ueda (2003): Eastern off Izu Peninsula – So far and hereafter –, Chikyu Monthly, **283**, 41-46. (in Japanese)

Oki, S., Mk. Murakami, N. Watanabe, B. Urabe, and M. Miyawaki (2005): Topographic Change of the Summit Crater of the Asama Volcano during 2004 Eruption Derived from Repeated Airborne Synthetic Aperture Radar (SAR) Measurements, Kazan, **50**, (5), 401-410.

Ozawa, S., S. Miyazaki, T. Nishimura, M. Murakami, M. Kaidzu, T. Imakiire, and X. Ji (2004): Creep, dike intrusion, and magma chamber deflation model for the 2000 Miyake eruption and the Izu islands earthquakes, J. Geophys. Res., **109**, B02410, doi:10.1029/2003JB002601.

Tanada, T. and H. Watanabe (2003): An attempt to detect ground temperature and crustal movement changes during the 2001 Hakone earthquake swarm activity, using satellite imagery, Bull. Hot Springs Res. Inst., **35**, 9-16.(in Japanease)

Tanbo, T., T. Tanada, H. Ito and Y. Daita (2005): The crustal movement associated with the 2001 earthquake swarm activity of Hakone volcano detected by the EDM network, J. Geogr. Soc. Japan, **51**, 45-48. (in Japanese)

Ueda, H., E. Fujita, M. Ukawa, E. Yamamoto, M. Irwan, and F. Kimata (2005): Magma intrusion and discharge process at the initial stage of the 2000 activity of Miyakejima, Central Japan, inferred from tilt and GPS data, Geophys. J. Int., **116**, 891-906.

Ukawa, M., E. Fujita, H. Ueda, T. Kumagai, H. Nakajima, and H. Morita (2006): Long-term geodetic measurements of large scale deformation at Iwo-jima caldera, Japan, J. Volcanol. Geotherm. Res., **150**, 98-118.

Watanabe, T., T. Tabei, T. Matsushima, T. Kato, S. Nakada, M. Yoshimoto, R. Chong, and J. T. Camacho (2005): Geodetic constraints for the mechanism of Anatahan eruption of May 2003, J. Volcanol. Geotherm. Res., **146**, 77-85.

Yamaoka, K., M. Kawamura, F. Kimata, N. Fujii, and T. Kudo (2005): Dike intrusion associated with the 2000 eruption of Miyakejima volcano, Japan, Bull. Volcanol., **67**, No.3, 231-242.

Yarai, H., Mk. Murakami, H. Mori, and J. Miyamoto (2005): Crustal deformation of Iwojima volcano detected by GPS campaign observations, J. Geogr. Surv. Inst., **106**, 51-55.

6.3 Periodic Movements

Heki (2004) investigated factors responsible for the seasonally changing coordinates of Japanese GPS points.

Tobita et al. (2004) investigated possible causes of seasonal groundwater level variation found in GPS continuous measurements. They found that groundwater pumping for paddy field irrigation during summer caused drawdown of groundwater level by 7 m and this caused temporal subsidence by about 2 cm at the GPS station in the campus of GSI, Tsukuba. The overall scale error of the GEONET due to the seasonal height variation of the fixed reference station at GSI is estimated to be ± 0.3 ppb. Munekane et al. (2004) investigated mechanism of these periodic vertical movements at Tsukuba and concluded that those are due to the elastic deformations in aquifers that are caused by the pore pressure changes induced by pumping of groundwater at nearby wells. They also investigated the periodic vertical movements that are observed in the GPS time series at the tip of the Tsukuba 32-m VLBI antenna. They found that the vertical movements are mainly due to the thermal expansion of the antenna.

Munekane and Matsuzaka (2004) studied the periodic vertical movements observed in the GPS time series on the Pacific islands. They found the periodic vertical movements are due to the non-tidal ocean loading.

Bibliography

Heki, K. (2004): Dense GPS array as a sensor of for seasonal changes of surface loads, in State of the Planet: Frontiers and Challenges in Geophysics, edited by R. S. J. Sparks and C.J. Hawkesworth, Geophys. Monograph Ser. **150**, 177-196, Am. Geophys. Union, Washington.

Munekane, H. and S. Matsuzaka (2004): Nontidal ocean mass loading detected by GPS observations in the tropical Pacific region, Geophys. Res. Lett., **31**, L08602, doi:10.1029/2004GL019773.

Munekane, H., M. Tobita, and K. Takashima (2004): Groundwater-induced vertical movements observed in Tsukuba, Japan, Geophy. Res. Lett., **31**, L12608, doi:10.1029/2004GL020158.

Tobita M., H. Munekane, M. Kaidzu, S. Matsuzaka, Y. Kuroishi, Y. Masaki, and M. Kato (2004): Seasonal Variation of Groundwater Level and Ground Level Around Tsukuba, J. Geod. Soc. Japan, **50**, 27-37. (in Japanese with English abstract)

6.4 In-situ Deformation Observations

NIED is operating the network of seismographs installed with a tiltmeter, and is monitoring crustal activity in and around Japan (Okada et al., 2004; Obara et al., 2005). One of importnat outcomes with the tiltmeter network is the detection of tilt changes with deep low frequency tremor activity, which are called short-term slow slip events

HSRI monitors crustal activity in western Kanagawa Prefecture in terms of borehole strainmeters and ground water levels (HSRI and Geological Survey of Japan, 2006a; 2006b). Daita et al. (2003) and Harada et al. (2004) researched the relationship between earth tide and the data of tiltmeter, Itadera (2003) and Harada et al. (2003) investigated thresholds for determining anomalies of groundwater and tiltmeter changes, respectively.

Recent development of in-situ measurement technology is remarkable. So-called Ishii-type bore instrument can be installed as deep as 1 km. Yamauchi et al. (2005) described the instrument and introduced some interesting results. One such instrument is installed in a borehole drilled through Nojima Fault, which ruptured in the 1995 Hyogo-ken Nanbu earthquake. Mukai and Fujimori (2003) reported temporal change in the permeability in fracture zone nearby Nojima Fault estimated using strain changes due to water injection experiments, which indicates a healing process of Nojima Fault.

Mukai and Fujimori (2005) re-determined the direction of the strainmeter. The strainmeter responds to geomagnetic changes because strain changes are measured with a magnetic sensor. We could determine direction of the strainmeter by the accuracy of several degrees using strain changes due to large geomagnetic disturbances.

Takemoto et al. (2003a; 2003b; 2004; 2005; 2006) installed a 100-m laser strainmeter system in a deep tunnel about 1000 m below the ground surface in Kamioka, Gifu, Japan. This strainmeter system has the resolving power of 10^{-13} in ground-strain measurements and the reliability to detect small strain changes of the order of 10^{-10} in the tidal frequency band. Hayakawa et al. (2006) developed an efficient method to convert the observed fringes to strain.

In order to detect “nucleation processes” of earthquakes, field experiments have been continued in gold mines in South Africa. Naoi et al. (2006) examined in high detail the continuous strain records for hundreds of events within Bambanani Mine, a deep gold mine of South Africa. Using an Ishii strainmeter installed at a seismically active part of the mine, they found strain release events that occurred over various lengths of time. About 70 % were normal earthquakes, while the remaining 24 % were slow-step events, which release strain silently without generating seismic shake. Some of the latter were preceded by nucleation. The authors anticipate that more spatially comprehensive work relating to mine-induced seismicity will shed light on natural earthquake generation processes.

A long-term, high-quality seismic ocean floor borehole observatory system, which includes strainmeter and tiltmeter, were developed and two observatories were installed in ocean bottom boreholes off Sanriku about 10 km above the seismogenic plate boundary (Araki et al., 2005).

Bibliography

Araki, E., M. Shinohara, S. Sacks, A. Linde, T. Kanazawa, H. Shiobara, H. Mikada, and K. Suyehiro (2004): Improvement of Seismic Observation in the Ocean by Use of Seafloor Borehole, Bull. Seism. Soc. Am., **94**, 678-690.

Daita, Y., T. Tanada, M.Harada, and H. Ito (2003): Verification of the borehole-type tiltmeters sensor azimuth in HSRl using tide and teleseismic, Bull. Hot Springs Res. Inst., **35**, 33-40.(in Japanease)

Harada, M., T. Tanada, H. Ito, and Y. Daita (2003): Experiment in discerning anomalous change on tiltmeter data employing STA/LTA ratio, Bull. Hot Springs Res. Inst., **35**, 41-46.(in Japanease)

Harada, M., T. Tanada, H. Ito, and T. Tanbo (2004): Earth tide observed at tiltmeter network of Hot Springs Research Institute of Kanagawa Prefecture, Bull. Hot Springs Res. Inst., **36**, 47-52.(in Japanease)

Hayakawa, H., S. Takemoto, S. Yoshii, A. Araya, A. Takamori, W. Morii, and M. Ohashi (2006): Improvement of the Fringe- to- Strain Conversion Method of Kamioka Laser Strainmeter, J. Geod. Soc. Japan, **52**, 183-193. (in Japanese with English Abstract)

Hot Springs Research Institute of Kanagawa prefecture and Geological Survey of Japan, AIST (2006a): Temporal variation in the groundwater level in the western part of Kanagawa prefecture, Japan (May 2005 – October 2005), Rep. Coord. Comm. Earthq. Pred., **75**, 245-247.

Hot Springs Research Institute of Kanagawa prefecture and Geological Survey of Japan, AIST (2006b): Temporal variation in the groundwater level in the western part of Kanagawa prefecture, Japan (November 2005 – April 2006), Rep. Coord. Comm. Earthq. Pred., **76**, 259-260.

Itadera, K. (2003): A simple method of correcting groundwater level observation data and thresholds for determining anomalies, Bull. Hot Springs Res. Inst., **35**, 47-52. (in Japanease)

Kawakata, H., H. Ogasawara, S. Sekiguchi, S. Uyama, and K. Mino (2006): Stress change prior to the major events in the 1989 earthquake swarm off the eastern Izu Peninsula, Japan, Earth Planets Space, **58**, 305-314.

Mukai, A. and K. Fujimori (2003): Permeability in Fracture Zone nearby the Nojima Fault Estimated Using Strain Changes due to Water Injection Experiments, Zisin 2, **56**, 171-179. (in Japanese with

English abstract)

Mukai, A. and K. Fujimori (2005): Calibration of the Measurement Direction of Strainmeters Installed at the 800m-deep Borehole in Awaji Island using Geomagnetic Disturbances, Zisin 2, **58**, 225-228. (in Japanese with English abstract)

Naoi, M., H. Ogasawara, J. Takeuchi, A. Yamamoto, N. Shimoda, K. Morishita, H. Ishii, S. Nakao, G. van Aswegen, A. J. Mendecki, P. Lenegan, R. Ebrahim-Trollope, and Y. Iio (2006): Small slow-strain steps and their forerunners observed in gold mine in South Africa, Geophys. Res. Let., **33**, L12304, doi: 10.1029/2006GL026507.

Obara, K., K. Kasahara, S. Hori, and Y. Okada (2005): A densely distributed high-sensitivity seismograph network in Japan: Hi-net by National Research Institute for Earth science and Disaster Prevention, Rev. Scientific Instruments, **76**, 021301doi:10.1063/1.1854197.

Ogasawara, H., J. Takeuchi, N. Shimoda, H. Ishii, S. Nakao, G. van Aswegen, A.J. Mendecki, A. Cichowicz, R. Ebrahim-Trollope, H. Kawakata, Y. Iio, T. Ohkura, M. Ando, and the Research Group for Semi-controlled Earthquake-generation Experiments in South African deep gold mines (2005a): High-resolution strain monitoring during M~2 events in a South African deep gold mine in close proximity to hypocentres, Proc. 6th Int. Symp. Rockburst and Seismicity in Mines, 385-391.

Ogasawara, H., J. Takeuchi, N. Shimoda, M. Nakatani, A. Kato, Y. Iio, H. Kawakata, T. Yamada, T. Yamauchi, H. Ishii, T. Satoh, K. Kusunose, K. Otsuki, S. Kita, S. Nakao, A. K. Ward, R. McGrill, S. K. Murphy, A. J. Mendecki, G. van Aswegen, and the Research Group for Semi-controlled Earthquake-generation Experiments in South African deep gold mines (2005b): Multidisciplinary monitoring of the entire life span of an earthquake and its practical strategy in South African gold mines, Proc. 6th Int. Symp. Rockburst and Seismicity in Mines, 393-398.

Okada, Y., K. Kasahara, S. Hori, K. Obara, S. Sekiguchi, H. Fujiwara, and A. Yamamoto (2004): Recent progress of seismic observation networks in Japan - Hi-net, F-net, K-NET and KiK-net -, Earth Planets Space, **56**, xv-xxviii.

Takemoto, S. (2005): Progress of Laser Strainmeter Observations in Japan, Annuals Disast. Prev. Res. Inst. Kyoto Univ., No. 48, B, 203-216. (in Japanese with English Abstract)

Takemoto, S., A. Araya, J. Akamatsu, W. Morii, T. Higashi, Y. Fukuda, K. Onoue, N. Ichikawa, I. Kawasaki, M. Ohashi, S. Terada, and H. Momose (2003a): Installation of 100m laser strainmeters in Kamioka Mine, Annuals Disast. Prev. Res. Inst. Kyoto Univ., No. 46, B, 749-755. (in Japanese with English Abstract)

Takemoto, S., H. Momose, K. Fujimori, and T. Higashi (2003b): Crustal Strain Observation with a Laser Extensometer in a Shallow Tunnel, J. Geod. Soc. Japan, **49**, 215-225. (in Japanese with English Abstract)

Takemoto, S., A. Araya, J. Akamatsu, W. Morii, H. Momose, M. Ohashi, I. Kawasaki, T. Higashi, Y.

Fukuda, S. Miyoki, T. Uchiyama, D. Tatsumi, H. Hanada, I. Naito, S. Terada, N. Ichikawa, K. Onoue, and Y. Wada (2004): A 100 m laser strainmeter system installed in a 1 km deep tunnel at Kamioka, Gifu, Japan, J. Geodynamics, **38**, 477-488.

Takemoto, S., H. Momose, A. Araya, W. Mori, J. Akamatsu, M. Ohashi, A. Takamori, S. Miyoki, T.Uchiyama, D. Tatsumi, T. Higashi, S. Terada, and Y. Fukuda (2006): A 100 m laser strainmeter system in the Kamioka Mine, Japan, for precise observations of tidal strains, J. Geodynamics, **41**, 23-29.

Yamauchi, T., H. Ishii, Y. Asai, M. Okubo, S. Matsumoto, and S. Azuma (2005): Development of deep borehole instruments for both multi-component observation and in situ stress measurement, and some interesting results obtained, Zisin 2, **58**, 1-14.

6.5 Geophysical Studies in Antarctica

Continuous GPS observation has been conducted since 1996 at Syowa Station (IGS site) and campaign GPS observations have also carried out at five sites on outcropped rocks in and around Syowa Station since 1998. VLBI experiments have been done six to ten times in a year since 1998. Fukuzaki et al. (2005) obtained lengths of three baselines, that is, Syowa-Hobart (Australia), Syowa-Hartebeesthoek (South Africa), Syowa-O'Higgins and their changes.

Ohzono et al. (2006) studied plate motion of the Antarctica based on GPS data analysis. The estimated plate motion is consistent with the previous studies and demonstrated a high rigidity of Antarctica Plate. In addition, they found a significant difference between GPS and VLBI results at Showa Station. They inferred a problem in VLBI measurement and suggested a local tie measurement between GPS and VLBI as a possible cause.

Bibliography

Fukuzaki, Y., K. Shibuya, K. Doi, T. Ozawa, A. Nothnagel, T. Jike, S. Iwano, D. L. Jauncey, G. D. Nicolson, and P. M. McCulloch (2005): Results of the VLBI experiments conducted with Syowa Station, Antarctica, J. Geod., **79**, 379-388.

Ohzono, M., T. Tabei, K. Doi, K. Shibuya, and T. Sagiya (2006): Crustal movement of Antarctica and Syowa Station based on GPS measurements, Earth Planets Space, **58**, 795-804.

6.6 Sea-level Change and Post-glacial Rebound

Sato et al. (2006) have analysed the Ny-Ålesund VLBI data over the period August 1994 to May 2004. They obtained secular displacement rates relative to a NNR-NUVEL-1A reference frame of 0.2 ± 0.5 mm/yr, − 1.7 ± 0.5 mm/yr and 4.8 ± 1.1 mm/yr for the north, east and vertical directions, respectively. The corresponding GPS station displacement rates relative to the same reference frame for the north, east, and vertical directions are 0.2 ± 0.6 mm/yr, − 2.3 ± 0.6 mm/yr, and 6.4 ± 1.5 mm/yr at NYA1 and − 0.1 ± 0.5 mm/yr, − 1.6 ± 0.5 mm/yr, and 6.9 ± 0.9 mm/yr at NALL, where these GPS rates were derived from the ITRF2000 velocity solution by Heflin. From the comparison at 25 globally distributed collocated sites, they found that the difference in uplift rate between VLBI and GPS at Ny-Ålesund is mainly due to a GPS reference frame scale rate error corresponding to 1.6 mm/yr in the GPS vertical rates. The uplift rate was estimated to be 5.2 ± 0.3 mm/yr from the analysis of the tide gauge data at Ny-Ålesund. Hence the uplift rates obtained from three different kinds of data are very consistent each other. The absolute gravity measurements at Ny-Ålesund, which were carried out four times (period: 1998–2002) by three FG5s, lead to a decreasing secular rate of − 2.5 ± 0.9 micro-gal/yr (1 micro-gal = 10^{-8} m/s^2). In this analysis, the actual data obtained from a superconducting gravimeter at Ny-Ålesund were used in the corrections for the gravity tide (including the ocean tide effect) and for the air pressure effect. They have estimated three geophysical contributions to examine the observed rates: (1) the effect of the sea-level (SL) change on a timescale of a few decades, (2) the effect of the present-day ice melting (PDIM) in Svalbard and (3) the sensitivity of the computed PGR effects to different choices of the models of past ice history and Earth's viscosity parameters. Their analysis indicates that the effect of SL change can be neglected as the main source of the discrepancy. On the other hand, the effect of PDIM cannot be ignored in explaining the mutual relation between the observed horizontal and vertical rates and the predicted ones. A large melting rate of the order of − 75 cm/yr (i.e. roughly 1.6 times larger than the mean rate derived from glaciology over Svalbard) would explain the observed uplift but only half of the gravity changes. Their comparison results clearly point out the importance of both the estimation accuracy of the elastic deformations and better observation accuracy to constrain the size of PGR effects in the northwestern Svalbard more tightly.

Bibliography

Sato, T., J. Okuno, J. Hinderer, D. S. MacMillan, H. -P. Plag, O. Francis, R. Falk, and Y. Fukuda (2006): A geophysical interpretation of the secular displacement and gravity rates observed at Ny-Alesund, Svalbard in the Arctic - Effects of the post-glacial rebound and present-day ice melting -, Geophys. J. Int., **165**, 729-743.

7. Marine Geodesy

Japan is surrounded by the ocean and there are active plate boundaries under the sea. So marine geodetic control is of an essential importance for Japan, and in these days, various challenges have been conducted to monitor crustal movement and deformation at the ocean bottom.

7.1 Marine Geodetic Control

Studies on marine geodetic controls are done mainly by JHOD. They are responsible for issuing nautical charts, which employed world geodetic system in 2002. Their SLR observation and data processing contributed to the establishment of the world geodetic system as the national geodetic coordinate system of Japan (Satellite Laser Ranging Group of the Japan Coast Guard, 2006). Their research activities also include positioning of remote islands, and laser ranging observations using a mobile SLR system have been done for two decades (Hydrographic and Oceanographic Department, 2003a; 2003b; 2005; Sato et al, 2004).

OBP gauges deployed off Kushiro recorded vertical crustal movement and tsunami associated with some earthquakes including the 2003 Tokachi-oki earthquake and its afterslip (e.g., Hirata et al., 2003; Baba et al., 2006; Mikada et al., 2006). A noise reduction method has been developed for such pressure gauges (Hirata and Baba, 2006). The off shore data of OBP gauges can also be used to estimate tsunami magnitude (Baba et al., 2004).

7.2 Sea-floor Geodesy

Apart from activities based on subaerial geodetic techniques, importance of seafloor positioning has been increasingly recognized by crustal deformation researchers. JHOD has been engaged in developing in-situ observation of seafloor crustal movement. Toyama et al. (2005) conducted experiments of precise direct path acoustic ranging at sea floor in and around Sagami Bay. For these several years, GPS/Acoustic technology for precise positioning of a seafloor reference point has progressed remarkably. JHOD and the Institute of Industrial Science, the University of Tokyo has been carrying out GPS/Acoustic seafloor geodetic observation since 2000 (e.g. Fujita, 2003; 2006; Fujita et al., 2006a, 2006b; Mochizuki et al., 2003; 2005). They have been carefully examining their methodology (e.g. Fujita and Yabuki, 2003; Fujita and Sato, 2004; Sato and Fujita, 2004; Ishikawa et al., 2006; Kawai et al., 2006), and making effort of improving their observation equipment (e.g. Unemi, 2004; Narita et al., 2005) and method of data analysis (e.g. Toyama, 2003; Fujita et al., 2004; Ishikawa and Fujita, 2005; Matsumoto et al., 2006). Their observation has revealed an intraplate crustal movement of 7.3 cm/yr WNW relative to the stable part of Eurasian Continent at a seafloor reference station located off Miyagi Prefecture, landward of Japan Trench (Fujita et al., 2006b). As a new-generation technique of seafloor geodetic observation, they have started to develop unmanned seafloor geodetic observation system applying Autonomous Underwater Vehicle (AUV) (Asada et al., 2005), and conducted the first field experiment in Sagami Bay in May 2006 (Asada et al., 2006; Mochizuki et al., 2006).

Tohoku University developed a seafloor positioning system with the GPS/Acoustic technology in cooperation with Scripps Institution of Oceanography, University of California, San Diego to investigate dynamics in the subduction zone. Kido et al. (2006) observed a large southward seafloor displacement of about 30 cm associated with the 2004 off the Kii Peninsula earthquake, which occurred in September 2004, between two survey campaigns in August and November 2004. The observed seafloor displacement is larger than that predicted from a slip model derived solely from GPS measurements on land. This indicates the GPS/Acoustic system is potential to reinforce source models of interplate earthquakes that occur far from the land GPS network.

Nagoya University is developing a different methodology of GPS/Acoustic measurement for detecting seafloor crustal deformation. Nishimura et al. (2005) demonstrated the effectiveness of seafloor geodetic measurements for improving spatial resolution of fault slip distribution at the Nankai Trough. Xu et al. (2005) conducted a simulation study for the optimum design of acoustic measurement to estimate the precise 3-D location of a seafloor station. Tadokoro et al. (2006) successfully detected a coseismic displacement associated with the 2004 Off the Kii Peninsula earthquake, demonstrating an importance of offshore geodetic observation near the source region in resolving the source mechanism.

Observation in southern East Pacific Rise recorded pressure increase at almost the same time as the termination of the 1997-98 El Nino (Fujimoto et al., 2003). It was also coincident with a remarkable change in the J_2 term of the Earth's gravity field. The local pressure variation across the spreading axis suggested thermal contraction of the crust in the inter-eruption period.

Bibliography

Asada, A., T. Ura, M. Mochizuki, K. Asakawa, and M. Fujita (2005): Development of unmanned seafloor geodetic observation system based on technologies of underwater robotics and seafloor platform, Chikyu Monthly, supplement **51**, 199-203. (in Japanese)

Asada, A., T. Ura, J. Han, M. Mochizuki, M. Fujita, T. Nakagawa, T. Tanaka, H. Zheng, T. Obara, and K. Nagahashi (2006): First sea-trial of advanced seafloor geodetic observation system using autonomous underwater vehicle, Proc. Mar. Acoust. Soc. Japan, 2006, 89-92. (in Japanese)

Baba T., K. Hirata, and Y. Kaneda (2004): Tsunami magnitudes determined from ocean-bottom pressure gauge data around Japan, Geophys. Res. Lett., **31**, L08303, doi:10.1029/2003GL019397.

Baba, T., K. Hirata, T. Hori, and H. Sakaguchi (2006): Offshore geodetic data conducive to the estimation of the afterslip distribution following the 2003 Tokachi-oki earthquake, Earth Planet.

Sci. Lett., **241**, 281-292.

Fujimoto, H., M. Mochizuki, K. Mitsuzawa, T. Tamaki, and T. Sato (2003): Ocean bottom pressure variations in the southeastern Pacific following the 1997-98 El Niño event, Geophys. Res. Lett., **30**, (9), 1456, doi:10.1029/2002GL016677.

Fujita, M. (2003): Seafloor geodetic observation - GPS/acoustic combination technique -, Hydro Int., **7**, 41-43.

Fujita, M. (2006): GPS/Acoustic seafloor geodetic observation – Progress by the Japan Coast Guard (review)-, Rep. Hydrogr. Oceanogr. Res., **42**, 1-14. (in Japanese with English abstract)

Fujita, M. and M. Sato (2004): Examination on repeatability of precise seafloor positioning, Rep. Hydrogr. Oceanogr. Res., **40**, 85-92. (in Japanese with English abstract)

Fujita, M. and T. Yabuki (2003): A way of accuracy estimation of K-GPS results in the seafloor geodetic measurement, Tech. Bull. Hydrogr. Oceanogr., **21**, 62-66. (in Japanese)

Fujita, M., M. Sato, and T. Yabuki (2004): Development of seafloor positioning software using inverse method, Tech. Bull. Hydrogr. Oceanogr., **22**, 50-56. (in Japanese)

Fujita, M., T. Ishikawa, M. Mochizuki, M. Sato, S. Toyama, M. Katayama, Y. Matsumoto, T. Yabuki, A. Asada, and O. L. Colombo (2006a): GPS/Acoustic seafloor geodetic observation: method of data analysis and its application, Earth Planets Space, **58**, 265-275.

Fujita, M., Y. Matsumoto, T. Ishikawa, M. Mochizuki, M. Sato, S. Toyama, K. Kawai, T. Yabuki, A. Asada, and O. L. Colombo (2006b): Combined GPS/Acoustic seafloor geodetic observation system for monitoring off-shore active seismic regions near Japan, Proc. ION GNSS-2006, Fort Worth, Texas.

Hirata, K. and T. Baba (2006): Transient thermal response in ocean bottom pressure measurement, Geophys. Res. Lett., **33**, L10606, doi:10.1029/2006GL026084.

Hirata, K., H. Takahashi, E. Geist, K. Satake, Y. Tanioka, H. Sugioka, and H. Mikada (2003): Source depth dependence of micro-tsunamis recorded with ocean-bottom pressure gauges:the January 28, 2000 Mw6.8 earthquake off Nemuro peninsula, Japan, Earth Planet. Sci. Lett., **208**, 305-318.

Hydrographic and Oceanographic Department (2003a): DATA Rep. Hydrogr. Observ., Ser. Satellite Geod., **15**. (in Japanese)

Hydrographic and Oceanographic Department (2003b): DATA Rep.Hydrogr. Observ., Ser. Satellite Geod., **16**. (in Japanese)

Hydrographic and Oceanographic Department (2005): DATA Rep. Hydrogr. Observ., Ser. Satellite Geod., **18**. (in Japanese)

Ishikawa, T. and M. Fujita (2005): Inverse method and precision improvement for seafloor positioning, Rep. Hydrogr. Oceanogr. Res., **41**, 27-34. (in Japanese with English abstract)

Ishikawa, T., M. Fujita, and Y. Matsumoto (2006): The influence of underwater temperature structure on seafloor positioning, Rep. Hydrogr. Oceanogr. Res., **42**, 15-29. (in Japanese with English abstract)

Kawai, K., M. Fujita, T. Ishikawa, Y. Matsumoto, and M. Mochizuki (2006): Accuracy evaluation of the long baseline KGPS, Tech. Bull. Hydrogr. Oceanogr., **24**, 80-88. (in Japanese)

Kido, M., H. Fujimoto, S. Miura, Y. Osada, K. Tsuka, and T. Tabei (2006): Seafloor displacement at Kumano-nada caused by the 2004 off Kii Peninsula earthquakes, detected through repeated GPS/Acoustic surveys, Earth Planet Science, **58**, 911-915.

Matsumoto, Y., M. Fujita, K. Kawai, T. Ishikawa, T. Yabuki, M. Mochizuki, and A. Asada (2006): Utilization of GPS antenna on the mast for seafloor geodetic observation, Tech. Bull. Hydrogr. Oceanogr., **24**, 94-98. (in Japanese)

Mikada, H., K. Mitsuzawa, H. Matsumoto, T. Watanabe, S. Morita, R. Otsuka, H. Sugioka, T. Baba, E. Araki, and K. Suyehiro (2006): New discoveries in dynamics of an M8 earthquake -Phenomena and their implications from the 2003 Tokachi-oki Earthquake using a long term monitoring cabled observatory-, Tectonophys., **426**, 95-105.

Mochizuki, M., Z. Yoshida, A. Asada, M. Sato, M. Katayama, and T. Yabuki (2003): Construction of seafloor geodetic observation network around Japan, Recent advances in marine science and Technology, 2002, 591-600.

Mochizuki, M., M. Fujita, M. Sato, Z. Yoshida, M. Katayama, T. Yabuki, and A. Asada (2005): Repeated trials of seafloor geodetic observation around Japan, Recent advances in marine science and technology, 2004, 11-18.

Mochizuki, M., A. Asada, T. Ura, M. Fujita, and O. L. Colombo (2006): New-generation seafloor geodetic observation system based on technology of underwater robotics, EOS Trans. AGU, **87**(52), Fall Meet. Suppl., Abstract G23B-1275.

Narita, Y., J. Unemi, and M. Mochizuki (2005): The improvement of the seafloor geodetic observation system, Tech. Bull. Hydrogr. Oceanogr., **23**, 53-60. (in Japanese)

Nishimura, S., M. Ando, and K. Tadokoro (2005): An application of numerical simulation techniques to improve the resolution of offshore fault kinematics using seafloor geodetic methods, Phys. Earth Planet. Inter., **151**, 181-193, 2005.

Satellite Laser Ranging Group of the Japan Coast Guard (2006): Contribution to geodesy, orbit determination of artificial satellites, and establishment of the World Geodetic System as the national geodetic coordinate system of Japan by means of satellite laser ranging, J. Geod. Soc. Japan, **52**, 21-36. (in Japanese with English abstract)

Sato, M. and M. Fujita (2004): Effects of sound velocity profiles in the seafloor geodetic observation, Tech. Bull. Hydrogr. Oceanogr., **22**, 42-49. (in Japanese)

Sato, M., H. Fukura, and M. Fujita (2004): Horizontal motions derived from satellite laser ranging observations, Rep. Hydrogr. Oceanogr. Res., **40**, 73-84. (in Japanese with English abstract)

Tadokoro, K., M. Ando, R. Ikuta, T. Okuda, G. M. Besana, S. Sugimoto, and M. Kuno (2006): Observation of coseismic seafloor crustal deformation due to M7 class offshore earthquakes, Geophys. Res. Lett., **33**, L23306, doi:10.1029/2006GL026742.

Toyama, S. (2003): Analysis for acoustic data in sea bottom geodetic observation, Tech. Bull. Hydrogr. Oceanogr., **21**, 67-72. (in Japanese)

Toyama, S., T. Yabuki, K. Terai, and Y. Nagaya (2005): Precise direct path acoustic ranging at sea floor, Chikyu Monthly, supplement **51**, 193-198. (in Japanese)

Unemi, J. (2004): Overview of the seafloor geodetic observation – From the aspect of practical operations -, Tech. Bull. Hydrogr. Oceanogr., **22**, 33-41. (in Japanese)

Xu, P., M. Ando, and K. Tadokoro (2005): Precise, three-dimensional seafloor geodetic deformation measurements using difference techniques, Earth Planets Space, **57**, 795–808.

8. Earth Tides and Ocean Tidal Loading

Takiguchi and Fukuda (2006) and Takiguchi et al. (2006) reported that the corrections of loading influences on GPS and SLR positioning were evaluated for several combinations of the geophysical fluid loads. They showed that the influence of the non-tidal ocean load was the largest of all the loads. They also applied the loading correction to the data of the 1997 Bungo Channel slow slip event and showed that the correction could benefit the analysis of such a non-periodic event.

Kobayashi et al. (2004) made a detailed coastline data set along Lutzow-holm Bay, Antarctica, and calculated oceanic tidal effects for gravity, radial displacement and horizontal displacement at Syowa Station and nearby areas.

Mukai et al. (2004) investigated the effect of fluid core resonance on tidal strains data at the Rokko-Takao station, Kobe, Japan. Mukai et al. (2006) and Takemoto et al. (2006) reported tidal strains observed at the Chu-Chie station, Taiwan.

Munekane (2006) made comparison between the GRACE-derived mass variations with those observed at the OBP recorders deployed as tsunami gauges. He found good correlations between these time series. This result confirms the quality of the GRACE-derived ocean mass variations, and also shows the possibility of using tsunami gauges as a mean to calibrate the GRACE-derived mass variations if one selects sites appropriately.

Bibliography

Kobayashi, Y., S. Iwano, and Y. Fukuda (2004): Detailed Coastline Data around Syowa Station, Antarctica, and Calculation of the Oceanic Tidal Loading Effects, J. Geod. Soc. Japan, **50**, 17-26. (in Japanese with English Abstract)

Mukai, A., S. Takemoto, and T. Yamamoto (2004): Fluid Core Resonance Revealed from a Laser Extensometer at the Rokko-Takao Station, Kobe, Japan, Geophys. J. Int., **156**, 22-28.

Mukai, A., S. Takemoto, M. Lee, C. Y. Chen, M. C. Kao, T. Ikawa, T. Kuroda, T. Abe, and T. Higashi (2006): Inhomogeneous Tidal Strains Observed at the Chu-Chie Station, Taiwan, J. Geod. Soc. Japan, **52**, 103-113. (in Japanese with English Abstract)

Munekane, H. (2006): Varidation of the ocean mass variations from GRACE by tsunami gauges, EOS Trans. AGU, **87**(36), West. Pac. Geophys. Meet. Suppl., Abstract G34A-0064.

Takemoto, S., M. Lee, C.-Y. Chen, M.-C. Kao, A. Mukai, T. Ikawa, T. Kuroda, and T. Abe (2006): Tidal strain observations in Chu-Chie, Taiwan, J. Geodynamics, **41**, 198-204.

Takiguchi, H. and Y. Fukuda (2006): Reduction of Influences of the Earth's Surface Fluid Loads on GPS Site Coordinate Time Series, J. Geod. Soc. Japan, **52**, 141-154.

Takiguchi, H., T. Otsubo, and Y. Fukuda (2006): Mass-redistribution-induced crustal deformation of global satellite laser ranging stations due to non-tidal ocean and land water circulation, Earth Planets Space, **58**, e13-e12.

9. Earth Rotation

The present-day perturbations of the Earth's rotation are sensitive to the glacial isostatic adjustment (GIA) arising from the Late Pleistocene glacial cycles and also to the recent mass balance of polar ice caps. Nakada and Okuno (2003) evaluated the polar wander and the change of degree two harmonic of the Earth's geopotential ($\dot{J}_2$), proportional to the rotation rate, for four Late Pleistocene ice models. They examined these perturbations as a function of lower- and upper- mantle viscosities and lithospheric thickness and rheology (elastic or viscoelastic), in which a compressible Earth model with elasticity and density given by the seismological model PREM is used. By considering the observations and predictions including the GIA process arising from the Late Pleistocene ice and recent mass balance of polar ice caps, they discussed the recent mass balance of the Antarctic and Greenland ice sheets. Two solutions are obtained for source areas of the recent Antarctic melting.

Furuya (2005) showed that, when the damping term is proportional to the wobble amplitude, we need to multiply the standard excitation term by a correction factor so that we can exactly derive the observed excitation.

Masaki and Aoyama (2005) compared seasonal and non-seasonal atmospheric angular momentum (AAM) functions calculated from the NCEP/NCAR, NCEP-DOE and ECMWF reanalysis data and found differences between these AAM functions, due to differences in the wind data. Masaki (2006) compared atmospheric angular momentum functions calculated from the

NCEP/DOE and ERA-40 reanalysis data and showed that large differences arise from wind differences in the upper troposphere, especially over the tropics and the southern mid-latitudes.

Bibliography

Furuya, M. (2005): On the damping term in the polar motion equation, in Plag, H.-P., B. Chao, R. Gross, and T. van Dam (eds.), Proc. Workshop: Forcing of polar motion in the Chandler frequency band: a contribution to understanding interannual climate variations, Cahiers du Centre Européen de Géodynamique et de Séismologie, Walferdange, Luxembourg, **24**, 57-59.

Masaki, Y. (2006): Comparison of Two AAM Functions Calculated from NCEP/DOE and ERA-40 Reanalysis Data Sets, Proc. Journées 2005: Systèmes de Référence Spatio-Temporels, Sept. 19-21, 2005, Warsaw, Poland. (in press)

Masaki, Y. and Y. Aoyama (2005): Seasonal and Non-seasonal AAM Functions from Different Reanalysis Data Sets, in Plag, H.-P., B. Chao, R. Gross, and T. van Dam (eds.), Proc. Workshop: Forcing of polar motion in the Chandler frequency band: a contribution to understanding interannual climate variations, Cahiers du Centre Européen de Géodynamique et de Séismologie, Walferdange, Luxembourg, **24**, 103-108.

Nakada, M. and J. Okuno (2003): Perturbations of the Earth's rotation and their implications for the present-day mass balance of both polar ice caps, Geophys. J. Int., **152**, 124-138.

10. Application to Atmospheric, Ionospheric and Hydrological Researches

Signals of space geodetic techniques such as GPS and SAR transmit the Earth’s troposhere and ionosphere. Measurements with these techniques are affected by the tropospheric water vapor contents and the ionospheric electron contents, and in turn, we can utilize geodetic techniques to estimate those parameters, which are very useful in meteorology and aeronomy. For this purpose, various observations as well as data analyses have been conducted.

Japanese geodesists carried out the Tsukuba GPS dense network campaign in collaboration with meteorologist in order to investigate local scale perturbation of water vapor and its effect on the positioning error (Aonashi et al., 2004; Shoji et al., 2004). Ichikawa et al. (2004) investigated GPS positioning errors due to the horizontal variability of water vapor content using a non-hydrostatic numerical weather model at 1.5 km grid spacing.

Hatanaka (2003) found that there are small annual signals in the north-south component of troposphere gradients and nearly half of the annual variation of network scale of the routine solution of GEONET is explained by effect of tropospheric gradient, which is neglected in the routine analysis. Yamagiwa and Hatanaka (2003) derived troposphere mapping functions from numerical weather models of JMA, and found small deviation from the mapping function of Niell (1996) which contains nominal seasonal variation.

Miyazaki et al. (2003) estimated tropospheric delay gradient as well as tropospheric zenith delay. The gradient shows a remarkable correspondence to the positioning error, which would appear without gradient estimation. This result suggests that, under a certain weather condition, gradient estimation is critical to precise positioning.

Shizuoka University performed GPS measurements at some stations in Southeast Asia to investigate water vapor changes in the tropic region with some research institutes (Horikawa et al., 2004; Satomura et al., 2003; 2004). They also repeated GPS measurements in a mountain area of central Japan to investigate the reason why GPS is less accurate in mountain areas. Relations of the coordinates obtained and zenith tropospheric delays were examined, and the results showed that their relations were different by the shape of the valleys (Satomura et al., 2005). Seko et al. (2004) investigated large GPS position errors that occurred concomitant with a mountain lee wave. The coincidence between the large position errors and the mountain lee wave suggests that small-scale fluctuations in water vapor and air density associated with lee waves could cause large positioning errors.

Yamanokuchi et al. (2005) estimated grounding line precisely in ice shelf zones from 25˚W to 40˚E of Antarctica by InSAR using SAR data acquired in ERS-1/2 tandem mission. Furuya and Wahr (2005) detected ground displacements around an ice-dammed lake (Lake Tiningnilik) in west Greenland, using ERS1/2 and Envisat radar interferograms and associated those displacements with draining episodes (jokulhlaups in Icelandic) that occurred in 1993 and 2003.

In September 2005, 15 continuous days of VLBI data were observed in the continuous VLBI 2005 (CONT05) campaign. Ichikawa et al. (2006) compared the zenith troposphere delay obtained from microwave water vapor radiometer (WVR) with concurrent observations made over the 15-day period by radiosonde, GPS, and VLBI in order to evaluate atmospheric delay effects on the VLBI experiment.

Tanaka (2007) monitored total water vapor contents along lines of sight at such low elevation angles as 10 and 15 degrees with two water vapor radiometers, WVR1100TM, WVR05 and 06. They were installed in two directions of N-S and E-W in Uji city, southwest Japan, in the period from 1997 to 1999. Results show that differences of wet delays between N and S directions, which correspond to the gradient of wet delays of microwaves, sometimes reach to 3 cm or more and continue to exist stably for a few days or longer. It is ascertained that the horizontal gradient of water vapor distribution in the N-S direction is caused by atmospheric conditions, especially by wind direction and velocity, and also probably by sunlight. Similar correlations are apparent between E-W gradients of wet delay and wind velocity. However, the data is not enough to draw definite conclusions on the E-W component.

As for the ionospheric studies, Heki and Ping (2005) studied coseismic ionospheric disturbance using GEONET for the 2003 Tokachi-oki earthquake. Heki et al. (2006) investigated the source process of the 2004 Sumatra-Andaman earthquake using coseismic ionospheric disturbances observed with GPS stations in SE Asia. Heki (2006) also discovered ionospheric disturbance caused by volcanic explosion using GEONET.

Sekido et al. (2003) evaluated the accuracy of total electron content (TEC) derived from GPS measurements by comparison with TEC obtained from continuous VLBI observations. A study team comprised of scientists at Institute de Physique de Globe de Paris, France (IPGP), California Institute of Technology, USA and GSI detected gravity waves excited by tsunamis detecting the propagation of TEC anomaly in the ionosphere using the continuous GPS measurements data.

Munekane (2005) studied the semi-annual scale changes observed by GEONET. He developed a semi-analytical method to estimate the effect of the second-order ionospheric delay on GPS positioning, and with the method, he showed that the semi-annual scale changes are mainly due to the second-order ionospheric delay.

A study team comprised of scientists at IPGP and GSI developed a method described in Houlie et al. (2005) to map temperature distribution in a volcanic plume during an eruption. They used propagation delay anomaly detected in the continuous GPS data. They applied the technique to the plume of 2000 August eruption of Miyake-jima Volcano and mapped 3-D temperature distribution.

GSI conducted a continuous monitoring of geomagnetism at Kanozan, Mizusawa and Esashi Geomagnetic Observatories, 11 continuous permanent stations, as well as campaign observations (repeated regularly over years) at 52 stations distributed in the country during 2003-2006. The observation data are published yearly in the periodical annual report of geomagnetic observations by GSI. GSI made a numerical model to represent a standardized geomagnetic field of Japan and a time dependent model to represent spatio-temporal evolution of geomagnetism around Japan.

Bibliography

Aonashi, K., T. Iwabuchi, Y. Shoji, R. Ohtani, and R. Ichikawa (2004): Statistical Study on Precipitable Water Content Variations Observed with Ground-Based Microwave Radiometers, J. Meteor. Soc. Japan, **82**, No. 1B, 269-275.

Artru, J., V. Ducic, H. Kanamori, P. Lognonné, and M. Murakami (2005): Ionospheric detection of gravity waves induced by tsunamis, Geophy. J. Int, **160**, 840-848, 2005.

Furuya, M. and J. M. Wahr (2005): Water level changes at an ice-dammed lake in west Greenland inferred from InSAR data, Geophys. Res. Lett., **32**, L14501, doi:10.1029/2005GL023458.

Hatanaka, Y. (2003): Estimation of Troposphere Delay and Accuracy of GEONET Solutions, Proc. Int. Workshop on GPS Meteorology – GPS Meteorology: Ground-Based and Space-borne Applications-, Jan. 14-17, 2003, Tsukuba, Japan, Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Int. Sci. Technol. Exchange Center (JAMSTEC), No. 1-02, 1-6.

Heki, K. (2006): Explosion energy of the 2004 eruption of the Asama Volcano, Central Japan, inferred from ionospheric disturbances, Geophys. Res. Lett., **33**, L14303, doi:10.1029/2006GL026249.

Heki, K. and J. -S. Ping (2005): Directivity and apparent velocity of the coseismic ionospheric disturbances observed with a dense GPS array, Earth Planet. Sci. Lett., **236**, 845-855.

Heki, K., Y. Otsuka, N. Choosakul, N. Hemmakorn, T. Komolmis, and T. Maruyama (2006): Detection of ruptures of Andaman fault segments in the 2004 Great Sumatra Earthquake with coseismic ionospheric disturbances, J. Geophys. Res., **111**, B09313, doi:10.1029/2005JB004202.

Horikawa, M., M. Satomura, S. Shimada, S. Kingpaiboon, T. Nakaegawa, T. Kato, and T. Oki (2004): Precipitable water vapor obtained by means of GPS at Khon Kaen, Thailand, Geosci. Rep. Shizuoka Univ., **31**, 33-39. (in Japanese)

Houlié, N., P. Briole, A. Nercessian, and M. Murakami (2005): Sounding the plume of the August 18, 2000 eruption of Miyakejima volcano (Japan) using GPS, Geophys. Res. Lett., **32**(5), L05302, doi:10.1029/2004GL021728

Ichikawa, R., H. Seko, and M. Bevis (2004): An evaluation of geodetic positioning error simulated using a mesoscale nonhydrostatic model, in M. Bevis, Y. Shoji, and S. Businger (eds.): Proc. SPIE, **5661**, Remote Sensing Applications of the Global Positioning System, 37-45.

Ichikawa, R., H. Kuboki, M. Tsutsumi, and Y. Koyama (2006): Zenith wet delay comparisons at Tsukuba and Kashima VLBI stations during the CONT05 VLBI campaign, IVS NICT-TDC News, **27**, 19-22.

Ji, X., M. Utsugi, H. Shirai, A. Suzuki, J. He, S. Fujiwara, and Y. Fukuzaki (2006): Modelling of spatial-temporal changes of the geomagnetic field in Japan, Earth Planets Space, **58**(6), 757-763.

Ji, X., H. Shirai, A. Suzuki, J. He, and H. Hamazaki (2006): Reduction of the data from the first-order geomagnetic stations with Natural Orthogonal Components method, J.Geogr. Surv. Inst., **110**, 27-32. (in Japanese)

Ji, X., H. Shirai, M. Watanabe, J. He, H. Nakagawa, and M. Utsugi (2004): The geomagnetic model in Japan area based on the continuous observation data, J. Geogr. Surv. Inst., **103**, 89-97. (in Japanese)

Ji, X., H. Shirai, A. Suzuki, J. He, and M. Utsugi (2004): Three components (X, Y, Z) Regional Model of Geomagnetic Field Changes in Japan with the Continuous observation data, Proc. XIth IAGA workshop on geomagnetic observatory instruments, data acquisition and processing, 290-295.

Miyazaki, S., T. Iwabuchi, K. Heki, and I. Naito (2003): An impact of estimating tropospheric delay gradients on precise positioning in the summer using the Japanese nationwide GPS array, J.

Geophys. Res., **108**, B7, doi:10.1029/2000JB000113.

Munekane, H. (2005): A semi-analytical estimation of the effect of second-order ionospheric correction on the GPS positioning, Geophy. J. Int., **163**, 10-17.

Nishimura, M., T. Iwabuchi, I. Naito, and M. Satomura (2003): Recomparison of GPS retrieved precipitable water vapor with radiosonde observation, Tenki, **50**, 909-918. (in Japanese)

Satoh, H., T. Yutsudo, T. Kadowaki, M. Ishihara, and S. Fujiwara (2003): Monitoring of crustal resistivity variations using a stationary wideband MT measurement system, J. Geogr. Surv. Inst., **101**, 23-32. (in Japanese)

Satomura, M., M. Fujita, F. Kimura, T. Nakaegawa, and T. Kato (2003): Precipitable water vapor variation obtained from GPS data in Thailand, Proc. 2002 Workshop on GAME-Tropics and Hydrometeorological Studies in Thailand and Southeast Asia, Oct. 29-31, 2002, Chiang Rai, Thailand, 165-167.

Satomura, M., S. Kingpaiboon, M. Horikawa, T. Nakaegawa, and S. Shimada (2004): Precipitable water vapor change obtained from GPS data at Khon Kaen in Thailand, Proc. 2003 Int. Symp. on the Climate System of Asian Monsoon and Its Interaction with Society, Nov. 11-13, 2003, Khon Kaen, Thailand, 270-271.

Satomura, M., S. Shimada, Y. Goto, and M. Nishikori (2005): GPS measurements to investigate the reason why GPS is less accurate in mountain areas, in F. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 44-47.

Sekido, M., T. Kondo, M. Imae, and E. Kawai (2003): Evaluation of GPS-based ionospheric TEC map by comparison with VLBI data, Radio Science, **38**, No.4, 1069.

Seko, H., H. Nakamura, and S. Shimada (2004): An evaluation of atmospheric models for GPS data retrieval by output from a numerical weather model, J. Meteor. Soc. Japan, **82**, 339-350.

Shirai, H. and A. Suzuki (2004): Geomagnetic Survey by Geographical Survey Institute in Japan, Proc. XIth IAGA workshop on geomagnetic observatory instruments, data acquisition and processing, 256-260.

Shoji, Y., H. Nakamura, T. Iwabuchi, K. Aonashi, H. Seko, K. Mishima, A. Itagaki, R. Ichikawa, and R. Ohtani (2004): Tsukuba GPS Dense Net Campaign Observation: Improvement in GPS Analysis of Slant Path Delay by Stacking One-way Postfit Phase Residuals, J. Meteor. Soc. Japan, **82**, No. 1B, 301-314.

Sugawara, Y., T. Kadowaki, and T. Kawahara (2004): Preliminary Observation of Geomagnetic Field Using dIdD Magnetometer, Proc. XIth IAGA workshop on geomagnetic observatory instruments, data acquisition and processing, 165-167.

Tanaka, T. (2007): Correlation Analyses of Horizontal Gradients of Atmospheric Wet Delay versus Wind Direction and Velocity, Dynamic Planet, in P. Tregoning & C. Rizos(Eds.), IAG Symposia **130**, Springer, Chapter120, 853-858.

Utsugi, M., H. Shirai, M. Watanabe, X. Ji, J. He, T. Nishiki, H. Hamazaki, and S. Fujiwara (2003): Regional model of the geomagnetic field changes in and around Japan, J. Geogr. Surv. Inst., **102**, 11-19. (in Japanese)

Yamagiwa, A. and Y. Hatanaka (2003): Mapping functions generated from numerical model and their impact on seasonal variations in GPS analysis, Proc. Int. Workshop on GPS Meteorology – GPS Meteorology: Ground-Based and Space-borne Applications-, 14-17 Jan. 2003, Tsukuba, Japan, Ministry of Education, Culture, Sports, Science and Technology(MEXT) and Japan Int. Sci. Technol. Exchange Center (JAMSTEC), No. 1-30, 1-4.

Yamanokuchi, T., K. Doi, and K. Shibuya (2005): Validation of grounding line of the East Antarctic Ice Sheet derived by ERS-1/2 interferometric SAR data, Polar Geosci., **18**, 1-14.

11. Planetary Geodesy

SELENE (SELenological and ENgineering Explorer) is a mission compound in preparation for launch in 2007 by JAXA. It carries 15 different missions, two of which are gravimetric experiments using radio waves performed by NAOJ, JAXA and universities (Hanada et al., 2004; Iwata et al., 2004). The RSAT (Relay Satellite Transponder) mission will undertake 4-way Doppler measurements of the main orbiter through the Rstar sub-satellite. In addition to 2-way Doppler and ranging measurements of the satellites, this will realize the first direct observation of the gravity fields on the far side of the Moon. The VRAD (Differential VLBI Radio Source) mission involves observing the trajectories of Rstar and Vstar using differential VLBI with both a Japanese network (VERA), and an international network. The development of the onboard instruments has already been finished and proto-flight tests are continued under various conditions (Noda et al., 2005a). Test VLBI observations of orbiters with the international network have also been performed (Kikuchi et al., 2004). Technologies which contribute to improvement of the experiments have also been developed, such as precise positioning of spacecraft by multi-frequency VLBI (Kono et al., 2003; Kawano et al., 2004), attitude estimation for a spin stabilized spacecraft from Doppler shift (Kikuchi et al., 2003), new method of measuring phase characteristics of antenna using doppler frequency measurement technique (Liu et al., 2004), same-beam DVLBI technology (Kikuchi, 2006; Liu et al., 2006).

NAOJ is proposing a selenodetic mission, e.g. in-situ Lunar Orientation Measurement (ILOM) to study lunar rotational dynamics by direct observations of the lunar physical libration and the free librations from the lunar surface with an accuracy of 1 mas in the post-SELENE project (Kawano et al., 2003; Hanada et al., 2004; Noda et al., 2005b). Year-long trajectories of the stars provide information on various components of the physical librations and they can also be used to possibly detect the lunar free librations in order to investigate the lunar mantle and the liquid core. The PZT on the moon is similar to that used for latitude observations of the Earth. They have a prospect to attain an accuracy of positioning of better than 1 mas from simulated experiments in laboratory using a CCD (Yano et al., 2004; 2006).

Theoretical investigations related to ILOM mission have also been made, and numerical modeling of lunar multiphase interior dissipation and perspective observation of fine effects at lunar rotation and free modes libration of the three-layers moon with outer liquid and inner rigid core have been developed (Gusev et al., 2003; Gusev et al., 2004; Petrova et al., 2004; Gusev et al., 2005).

Harada and Kurita (2003; 2005) investigated the dependence of the surface tidal stress on the internal structure of Europa and suggested the possibility of the cracking at the icy shell, and also investigated the effect of the non-synchronous rotation on the surface stress of Europa and put constraints upon the rotation period and the surface viscosity.

Harada and Heki (2006) calculated secular obliquity variations due to climate friction on Mars and found that the effect of the climate friction became greater than that concluded by previous research under an internal structure with a visco-elastic crust and/or a solid core, and that the possibility of the great effect of the climate friction became stronger than that concluded by previous research under an internal structure with a heterogeneous mantle.

Bibliography

Gusev, A., N. Kawano, the RISE Project Group, and N. Petrova (2003): Gravitation Investigations on the SELENE mission and the existence of a lunar core, Astron. & Astroph. Trans., **22**, 579-584.

Gusev, A., N. Kawano, and N. Petrova (2004): Modeling of lunar multiphase interior dissipation and perspective observation of fine effects at lunar rotation, Proc. Int. Conf. "Modern direction of astronomical evolution in Russia", 269-274.

Gusev, A., N. Kawano, and N. Petrova (2005): Fine Phenomena of the lunar libration, 36th Lunar Planet. Sci. Conf., 1447, 1-2.

Hanada, H., K. Heki, H. Araki, K. Matumoto, H. Noda, N. Kawano, T. Tsubokawa, S. Tsuruta, S. Tazawa, K. Asari, Y. Kono, T. Yano, N. Gouda, T. Iwata, T. Yokoyama, H. Kanamori, K. Funazaki, and T. Miyazaki (2004): Application of PZT telescope to Insitu Lunar Orientation Measurement (ILOM), in F. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 163-168.

Harada, Y. and K. Heki (2006): Secular Obliquity Variations Due to Climate Friction on Mars: Re-Examination in Influence of Martian Internal Viscosity Structure, Proc. 38th ISAS Lunar and Planet. Symp. (2005), Inst. Space and Astronautical Sci. @ Japan Aerospace Exploration Agency, **38**, 232-235.

Harada, Y. and K. Kurita (2003): The Dependence of the Surface Tidal Stress on the Internal

Structure of Europa: On the Possibility of the Cracking at the Icy Shell, Proc. 36th ISAS Lunar and Planet. Symp. (2003), Inst. Space Astronautical Sci. @ Japan Aerospace Exploration Agency, **36**, 218-221.

Harada, Y. and K. Kurita (2005): The Effect of the Non-synchronous Rotation on the Surface Stress of Europa: Constraints for the Rotation Period and the Surface Viscosity, Proc. 37th ISAS Lunar and Planet. Symp. (2004), Inst. Space Astronautical Sci. @ Japan Aerospace Exploration Agency, **37**, 196-199.

Iwata, T., T. Sasaki, T. Izumi, Y. Kono, H. Hanada, N. Kawano, and F. Kikuchi (2004): Results of the critical design of RSAT/VRAD mission instruments on SELENE sub-satellites Rstar/Vstar for selenodesy, in F. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 157-162.

Kawano, N., H. Hanada, T. Tsubokawa, and T. Iwata (2003): Research on lunar interior by Japanese explorer SELENE, Proc. Geon-Kazan-2003 (New Geometry of Nature), 114-119.

Kawano, N., Y. Kono, J. Ping, K. Matsumoto, F. Kikuchi, and Q. Liu (2004): Narrow and width and INTERNET Linked VLBI (Very Long Baseline Interferometry) for Satellite Tracking, 24th Int. Symp. on Space Technol. Sci., (Miyazaki, May 30-June 6).

Kikuchi, F. (2006): Differential Phase Delay Estimation by Same-Beam VLBI Method, PhD thesis, the Graduate University for Advanced Studies, pp78.

Kikuchi, F., Y. Kono, H. Hanada, T. Iwata, T. Ono, and N. Kawano (2003): Attitude Estimation for a Spin Stabilized Spacecraft from Doppler Shift, IEICE Trans. Commun., **J86-B**, 959-968. (in Japanese)

Kikuchi, F., Y. Kono, M. Yoshikawa, M. Sekido, M. Ohnishi, Y. Murata, J. Ping, Q. Liu, K. Matsumoto, K. Asari, S. Tsuruta, H. Hanada, and N. Kawano (2004): VLBI observations of narrow bandwidth signals from the spacecraft, Earth Planets Space, **56**, 1041-1047.

Kono, Y., H. Hanada, J. Ping, Y. Koyama, Y. Fukuzaki, and N. Kawano (2003): Precise positioning of spacecraft by multi-frequency VLBI, Earth Planets Space, **55**, 581-589.

Liu, Q., S. Tsuruta, K. Asari, J. Ping, F. Kikuchi, K. Matsumoto, and N. Kawano (2004): New Method of Measuring Phase Characteristics of Antenna Using Doppler Frequency Measurement Technique, IEEE Trans. A&P, **52**, 3312-3318.

Liu, Q., K. Matsumoto, F. Kikuchi, J. Ping, K. Asari, H. Hanada, and N. Kawano (2006): Same-Beam Differential VLBI Tecknology Using Two Satellites of the SELENE Spacecraft, IEICE Trans. Commun., **J89-B**, 602-617. (in Japanese)

Noda, H., K. Asari, N. Namiki, T. Iwata, Y. Kono, H. Hanada, N. Kawano, and Z. Yamamoto (2005a): Ground-based verification of four-way Doppler measurement for the SELENE mission, in F. Sanso (ed.), IAG Symposia **128**, A Window on the Future of Geodesy, Springer, 152-156.

Noda, H., H. Hanada, T. Iwata, and N. Kawano (2005b): The SELENE mission and Japanese lunar exploration scenario, proceedings of the Sixth East Asian Meeting of Astronomy (EAMA6), J. Korean Astron. Soc., **38**, 311-314.

Petrova, N., N. Kawano, and A. Gusev (2004): SELENE-B: Numerical modeling of free modes libration of the three-layers Moon with outer liquid and inner rigid core, Proc. Int. Conf. Modern direction of astronomical evolution in Russia, 275-281.

Yano, T., N. Gouda, Y. Kobayashi, T. Tsujimoto, T. Nakajima, H. Hanada, Y. Kan-ya, H. Araki, S. Tazawa, K. Asari, S. Tsuruta, and N. Kawano (2004): CCD Centroiding Experiment for JASMINE (Japan Astrometry Satellite Mission) and ILOM (In-situ Lunar Orientation Measurement), Publ. Astron. Soc. Pacific, **116**, 667－673.

Yano, T., H. Araki, N. Gouda, Y. Kobayashi, T. Tsujimoto, T. Nakajima, N. Kawano, S. Tazawa, Y. Yamada, H. Hanada, K. Asari, and S. Tsuruta (2006): CCD centroiding experiment for correcting a distorted image on the focal plane, Publ. Astron. Soc. Pacific, **118**. (in press)