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# Report of the Geodetic Works in Japan for the Period from January 2007 to December 2010

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Contents

## 1. Introduction

This report summarizes the geodetic activities in Japan for the period from January 2007 to December 2010. It is to be submitted, on behalf of the National Committee for Geodesy, Earth and Planetary Science Committee, The Science Council of Japan, to the IAG General Assembly at the IUGG 2011 to be held in Melbourne, Australia, June–July 2011.

The Geodetic Society of Japan (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. A. Mukai, M. Fujita, A. Araya and T. Nishimura were the winners of the Tsuboi Prize, and The Group for Studies on Geodesy and Solid Earth Geophysics of Antarctica represented by K. Kaminuma, Project Team for GPS Meteorology represented by T. Iwabuchi and S. Shoji, InSAR Developing and Operating Group of ALOS/PALSAR System represented by M. Shimada, and RISE (Research in Selenodesy) project represented by N. Kawano, respectively, were the awardees for the Group Tsuboi Prize. GSJ also celebrates the best presentation student awards at its fall meeting. K. Kataoka, T. Hasegawa, T. Kazama, H. Sakayori, K. Matsuo, K. Takatsuka, M. Ozaki, M. Ohzono, I. Okazaki, and Y. Nakamura were the recipients of the best presentation awards in the last four years.

The period from 2007 to 2010 saw major progress in two space geodetic techniques in Japan. One is the L-band SAR with a satellite and the other the Japanese lunar mission. Both made significant and definitive contributions to advances in geodesy. Including these two, we mention below highlights of the geodetic research during the last four years.

### (1) L-band SAR

The Advanced Land Observing Satellite (ALOS, a.k.a. “Daichi”) was launched in January 2006 and has been operated by Japan Aerospace Exploration Agency (JAXA). This satellite is equipped with a Phased Array L-band Synthetic Aperture Radar (PALSAR). Owing to the nature of the L-band signal that penetrates the vegetation over the land surface, the ALOS/PALSAR provides fundamental data sets for monitoring the variability of the solid Earth, such as crustal deformation caused by seismic and volcanic activities. For example, the Geospatial Information Authority of Japan (GSI) analyzed crustal deformation caused by the Niigataken Chuetsu-oki Earthquake in 2007 using the InSAR data. The uplift motion associated with episodic growth of fault-related folds was discovered [1].

### (2) Selenodesy

The Japanese lunar mission SELENE (a.k.a. “Kaguya”) was launched in September 2007, and the mission ended in June 2009. Three selenodetic mission instruments were onboard, i.e., RSAT (satellite-to-satellite Doppler tracking system) and VRAD (VLBI radio sources) for gravity field recovery, and LALT (laser altimeter) for global topography observation. The tracking data provided by RSAT revealed detailed gravity features of the far side of the moon. Tracking of VRAD by international as well as domestic VLBI stations contributed to improved orbit consistency. A global lunar topographic map with a spatial resolution finer than 0.5 degrees was derived from LALT. The new data sets for lunar gravity and topography have been released from SELENE Level 2 database and used for geophysical researches of crustal thickness, structure and compensation states of impact basins, etc. [2].

(3) Positioning and Navigation

(3-1) Supplementation of GPS for Urban or Mountainous Areas

A quasi-zenith satellite “MICHIBIKI” was launched in September 2010. It has been injected into the quasi-zenith orbit over Japan with its center longitude of about 135°E. The satellite is now subject to initial functional verification, and is expected to supplement the GPS satellites for improved accuracy in positioning especially in urban or mountainous regions.

(3-2) Continuous GPS Observation Network

The Geospatial Information Authority of Japan modernized the strategy of its routine analysis of the Japanese continuous GPS observation network (GEONET: GPS Earth Observation Network System); the world’s largest regional GPS network, serves not only for geodesy but also for meteorology, seismology, volcanology and ionosphere sciences. The new analysis strategy (Version 4) adopts (i) estimation of atmospheric gradient, (ii) absolute antenna phase center models, (iii) coordinate system ITRF2005, (iv) new calculation method of fixed point and (v) new correction method of ionospheric delay. The quality of the estimated coordinates was significantly improved by adopting the new strategy [3].

(3-3) VLBI

National Institute of Information and Communications Technology (NICT) succeeded in developing technology for real-time data transmission of VLBI data over inter-continental baseline, which enables quick derivation of the earth rotation parameter UT1 [4].

The GSI operates Tsukuba 32-m VLBI station (TSUKUB32) and the Tsukuba VLBI data processing facility for international VLBI sessions [5].

(4) Analysis of GRACE data

GRACE monthly gravity data were analyzed to reveal that 40-50 gigatons of mountain glaciers are lost from the Himalayas and major mountain belts in central Asia [6]. Fairly large uncertainty comes from possible contribution from glacial isostatic rebound, separability from groundwater loss in northern India, and climate fluctuations in decadal timescales. This result suggests that, contrary to the prediction of IPCC, the glaciers in Himalayas may not be lost within 30 years.

Postseismic gravity (geoid height) change was detected for the first time in the world using GRACE monthly gravity data before and after the 2004 Sumatra-Andaman earthquake [7].

(5) Seafloor Crustal Movements by GPS/Acoustic Observation

Japan Coast Guard and The University of Tokyo made observations of seafloor crustal movements by the GPS/Acoustic method and detected a coseismic slip associated with the 2005 Off-Miyagi Prefecture Earthquake (M7.2), post-seismic slip until early 2007, and then recovery of coupling [8]. These observations indicate temporal changes in the coupling state in the seismogenic zone associated with the plate subduction.

(6) Dr. Tadahiro Sato Awarded The 4th Earth Tide Commission Medal

Dr. Tadahiro Sato, a visiting professor of Tohoku University, was awarded The 4th Earth Tide Commission Medal by the IAG Earth Tide Commission in 2008 for his wide range of contributions: from logistical and experimental work on instruments and stations through programming of extensive codes to the sophisticated analysis of data, from secular and multiannual signals through the diurnal tidal range to the free oscillations of the Earth and marine basins, and coseismic gravity changes, more than 6 orders of magnitude in frequency.

(7) Dr. Masato Furuya Wins The 2007 Guy Bomford Prize

Dr. Masato Furuya, now an associate professor at Hokkaido University, received the 2007 Guy Bomford Prize by the International Association of Geodesy in recognition of his outstanding and broad research in geodesy and the geophysical interpretation of data and results. His diverse contributions cover all the "three pillars" of geodesy, i.e., Earth rotation, gravity, and crustal deformation.

(8) The Passing of Leading Geodesists

During the last four years some leading scientists in geodesy passed away: Yoshifumi Tomoda (Member of National Academy of Japan, Emeritus Professor of University of Tokyo) on December 17, 2007; Takeshi Dambara (Former Professor, Shizuoka University) on August 6, 2009; Hiromichi Suzuki (Former Deputy Director of Geographical Survey Institute) on May 28, 2010; Yoshiteru Kono (Emeritus Professor, Kanazawa University) on November 22, 2010. The passing of these leading scientists reminds us of the glorious days of classical geodesy, in particular of gravimetry.

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## 2. Positioning

The Geospatial Information Authority of Japan (GSI) has been participating in International VLBI (Very Long Baseline Interferometry) Service for Geodesy and Astrometry, IVS, as an observing station, a correlation center, and an analysis center. GSI maintains Tsukuba 32-m VLBI station (TSUKUB32) and the Tsukuba VLBI data processing facility to operate the VLBI observation and data analysis for the international VLBI session. The major tasks assigned to GSI are the observation using the 32-m-diameter antenna, and the data processing and the analysis for the IVS intensive sessions (IVS-INT02), which are implemented for monitoring UT1-UTC on the baseline between TSUKUB32 and WETTZELL station in Germany. Every year, TSUKUB32 participated in more than 200 international VLBI sessions and GSI correlation center made data processing for about 100 international sessions. GSI also has three regional VLBI stations; Shintotsukawa 3.8-m station in Hokkaido, Aira 10-m station in Kagoshima, and Chichijima 10-m station in Ogasawara. These stations have participated in international VLBI sessions several times since 2008. GSI has also conducted geodetic VLBI sessions with TSUKUB32 and the three regional stations in order to control and monitor the consistency of the Geodetic Reference System of Japan. Ishii et al. (2009), Kokado et al. (2007; 2008), Kurihara and Kokado (2009), Kurihara and Matsuzaka (2009), Matsuzaka et al. (2008a; 2008b; 2008c), Miura et al. (2009a; 2009b), Nozawa et al. (2009), Shigematsu et al. (2007; 2008), and Tanimoto et al. (2007; 2008) reported these activities.

Hydrographic and Oceanographic Department, Japan Coast Guard (JHOD) has been carrying out monitoring of crustal movements through continuous GPS observations at DGPS stations and in Izu-Oshima area. The observation results in 2006, 2007 and 2008 are reported in Hydrographic and Oceanographic Department (2008; 2009; 2010).

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## 3. Development in Technology

### 3.1 VLBI

National Institute of Information and Communications Technology (NICT) has been contributing to developments of e-VLBI technology and standardization of data format for international VLBI data exchange. Realtime transmission of VLBI data over the inter-continental baseline demonstrated quick derivation of the earth rotation parameter UT1 (Koyama et al., 2008a; 2008c; Sekido et al., 2008a; 2008b; 2009; Matsuzaka et al., 2008). NICT and GSI have been actively involved into ultra-rapid UT1 experiments, demonstrating that this important Earth orientation parameter can be determined in near real-time using state of the art network infrastructures and processing techniques (Haas et al., 2010). Moreover, Hobiger et al. (2009b) discussed the effect of unmodeled station clock offsets on UT1 estimates and proposed a simple correction scheme for the case that these effects have not been considered in the analysis.

Development of the K5 VLBI system started in 1999 by Communications Research Laboratory (currently National Institute of Information and Communications Technology) (Kondo et al., 2008). One of the purposes for developing the K5 VLBI system was to realize real-time VLBI observation and correlation processing to be performed under different settings and modes according to the characteristics of the observing sessions. To fulfill this purpose, diverse component systems were developed to allow flexible combination of these components. The K5 system adopted the specifications of the VLBI Standard Interface (VSI), which were discussed and designed within the international VLBI community to allow easy interconnectivity between multiple components for VLBI observations (Koyama et al., 2008b). By applying the defined specifications of VSI, the K5 system has been used with other differently designed VLBI systems in the various international VLBI experiments. Kondo et al. (2009) and Hobiger et al. (2009c) deal with the usage of phase delays, which are expected to be one order of magnitude more accurate than the current group delay measurement.

NICT and GSI started to develop a compact VLBI system with a 1.6 m diameter aperture dish in order to provide reference baseline lengths for calibration (Ishii et al., 2007; Ichikawa et al., 2008c). The reference baselines are used to validate surveying instruments such as GPS (Global Positioning System) and EDM (Electro-Optical Distance Measurement) and maintained by GSI. Ishii et al. (2008) evaluated the Laser-pumped Cs Gas-cell frequency standard on geodetic VLBI experiments for mobile VLBI measurements using the compact VLBI system. The analyzed Kashima-Koganei baseline length (about 110 km) is well consistent with those obtained by the other VLBI measurements using a hydrogen frequency standard. Ishii et al. (2009) performed the geodetic VLBI experiments to evaluate the new front-end system using a wide-band quad-ridged horn antenna (ranging 2 – 18 GHz) by installing it on the 2.4 m diameter antenna at Kashima as a feasibility study. They concluded the new feed is well available for millimeter VLBI measurements.

Kawai et al. (2008) evaluated a state-of-the-art high-temperature superconductor (HTS) band-pass filter to mitigate severe radio frequency interference (RFI) due to a third-generation mobile phone system (IMT-2000). The S-band frequency used in the typical geodetic VLBI system severely suffered from such RFI. This device demonstrated a remarkable RFI mitigation.

Ichikawa et al. (2008a) demonstrated the availability of the numerical weather data to estimate atmospheric slant delays which cause severe positioning errors in VLBI and GNSS measurements. Hobiger et al. (2008a) presented the Kashima Ray-tracing tools (KARAT) which allow to compute ray-traced troposphere delay correction based on numerical weather model input. Such corrections have been successfully applied to GPS (Hobiger et al., 2008b; Ichikawa et al., 2008b; Hobiger et al., 2010c; Ichikawa et al., 2010), VLBI (Boehm et al., 2010) and InSAR (Hobiger et al., 2010b) leading to an improvement of the target parameters. A KARAT version running on a graphics processing unit (GPU) has been developed for real-time applications with a large number of stations (Hobiger et al., 2009a).

Graphics processing units (GPUs) offer plenty of parallel processing power which can be utilized to realize a software defined radio, without consuming much of the CPU processing time. Hobiger et al. (2010a) demonstrated how a software defined GPS receiver can be implemented on a GPU, yielding identical results to those a hardware receiver would provide. Currently, tests with a low-cost hardware front-end and sampler are under way, reducing the cost of the system and making it attractive for rapid prototyping and teaching purposes.

Hobiger et al. (2008c) suggested a constraint model for ionosphere tomography and a more realistic choice of the underlying Earth model (Hobiger et al., 2007a). VLBI can also be used as data source for monitoring the ionosphere, either as a single technique (Hobiger et al., 2007b) or in combination with other space geodetic techniques (Todorova et al., 2008).

Takiguchi et al. (2007) carried out geodetic VLBI experiments to compare the results with GPS and VLBI time transfer. The results of VLBI were very consistent with the results of GPS. The difference of the results was about ±500 picoseconds. In terms of frequency stability, the Allan deviation showed that VLBI is more stable than GPS between 2000 to 60000 seconds. Takiguchi et al. (2008) compared the frequency transfer precision between VLBI and GPS carrier phase using IVS and IGS observation data in order to confirm the potential of VLBI time and frequency transfer. The results show that VLBI time transfer is more stable than GPS time transfer on the same baseline and same period. Takiguchi et al. (2009) carried out a long term VLBI experiment together with GPS and DMTD measurement to show the frequency stability of local baseline. They compared the results obtained from these three techniques. The results are strongly correlated at a long term period. The frequency stability of VLBI is surpassing the stability of atomic fountain at $10^5$ seconds or longer.

Takiguchi et al. (2009) carried out the intercomparison experiments between VLBI, GPS and Dual Mixer Time Difference (DMTD) clock measuring system to show that VLBI can measure the right time difference. They produced the artificial change using line stretcher. At the artificial change part, VLBI and DMTD show a good agreement, less than 10 picoseconds. The quantity and sense of VLBI results match well with DMTD. Takiguchi et al. (2010) carried out an intercomparison experiment between VLBI and GPS to show that VLBI can measure the correct time difference. They produced an artificial delay change by stretching the Coaxial Phase Shifter. Concerning the artificial changes, VLBI and the nominal value of Coaxial Phase Shifter show good agreement, i.e. less than 10 picoseconds.

Hanada et al. (2008a; 2008b; 2009a; 2009b; 2010), Kikuchi et al. (2008b; 2009a; 2009b; 2009c) and Liu et al. (2009a; 2009b; 2010) carried out differential VLBI observations of Radio sources on-board the sub satellites, Rstar (Okina) and Vstar (Ouna) of SELENE (Kaguya) by the Japanese VERA (VLBI Exploration of Radio Astrometry) network and an international VLBI network in order to improve the lunar gravity field model. Kikuchi et al. (2008a) and Liu et al. (2007a; 2007b) developed the multi-frequency and the same-beam VLBI, which are the essential techniques for the successful observing program, and Kikuchi et al. (2009a) succeeded in correlating the recorded signals from Okina/Ouna, and obtained phase delays with an accuracy of several picoseconds at S-band.

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### 3.2 SLR

The Shimosato Hydrographic Observatory has been carrying out satellite laser ranging observation since 1982. In 2009, the satellite laser ranging system was thoroughly replaced. Suzuki et al. (2010) overviewed the present status and specification of the upgraded system.

Results of Satellite Laser Ranging observations by a fixed type satellite laser ranging station at the Shimosato Hydrographic Observatory (JHDLRS-1) are reported in Hydrographic and Oceanographic Department (2007; 2008; 2009; 2010). The total number of returns obtained by the JHDLRS-1 was 1,057,371 from 2,331 passes in 2005, 610,661 from 2,366 passes in 2006, 262,250 from 1,213 passes in

2007, and 157,823 from 606 passes in 2008, respectively.

In order to reduce the influence caused by variation of signal intensity, two new techniques were introduced at the Shimosato Hydrographic Observatory in 2006: namely, the methods named Triple Threshold Screening (TTS) and Constant Mid-signal Detection (CMD). Kurokawa et al. (2007b) showed the principle of these techniques and verified their effectiveness in improving the ranging accuracy.

Kurokawa et al. (2007a) described the history and effort to improve the accuracy about Satellite Laser Ranging observation at the Shimosato Hydrographic Observatory.

National Institute of Information and Communications Technology (NICT) and Hitotsubashi University have continuously provided daily quality control reports for worldwide satellite laser ranging stations for more than 10 years. Otsubo et al. (2008) presented the analysis flow and the feedback procedure with actual examples.

Optical responses of various types of retroreflectors are numerically simulated for future lunar laser ranging targets (Otsubo et al., 2010). Proper choice of dihedral angle offset is the key for a single reflector design larger than 100 mm of diameter.

The spin axis of the Japanese geodetic satellite AJISAI was determined by satellite laser ranging data for the first time (Kucharski et al., 2010). The solution reveals that the spin axis is precessing with a period of 117 days, equal to the period of the right ascension of the ascending node of its orbit.

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## 3.3 GPS

### 3.3.1 GEONET

GSI has been operating the nationwide GPS array known as the GPS Earth Observation Network system (GEONET) since 1996. Continuous GPS data from GEONET support and provide the reference for GPS surveying in Japan and yield daily time series of site coordinates for monitoring crustal deformations.

The GEONET routine analysis system has been reinforced and revised step by step. The first revision was done in 2001 (Hatanaka et al. (2003)), the second in 2004 (GSI (2004)) and the latest in 2008. Nakagawa et al. (2009) overviewed the modification of the latest revision such as updating a version of Bernese software from 4.2 to 5.0, estimating tropospheric delay gradients, introducing absolute antenna phase center variation (PCV) models, updating geodetic datum from ITRF2000 to ITRF2005 and altering a strategy of calculating coordinates of the base station in Tsukuba.

Iwashita et al. (2009) and Nogami et al. (2008) compared results from the former and current GEONET analysis strategy by processing the data of past earthquakes and volcanic activities in Japan. They indicated that the new strategy could be more sensitive to detect crustal movements with a scale of about 1 cm. By estimating the tropospheric delay gradients, Miyahara et al. (2008a) found that errors caused by climate condition, reported by Amagai et al. (2007), were reduced in most cases. Miyahara et al. (2009) reviewed all these results.

Ishimoto et al. (2007a) evaluated crustal deformations caused by the Noto Hanto Earthquake in 2007 by processing GEONET data and reported about 21 cm southwest movement at the Togi station in Ishikawa prefecture. Ishimoto et al. (2007b) found 17 cm northwest movement at the Kashiwazaki station in Niigata prefecture by the Niigataken Chuetu-oki Earthquake in 2007. Miyahara et al. (2008b) reported about 1.5 m southwest and 2.1 m uplift movement at the Kurikoma2 station in Miyagi prefecture by the Iwate-Miyagi Nairiku Earthquake in 2008.

Kotani et al. (2009) developed a new method to determine coordinates of the base station in the GEONET routine analysis by processing with about 20 IGS stations around Japan. They succeeded in eliminating influences caused by a seasonal local movement around the base station in Tsukuba.

Toyofuku et al. (2007) showed an advantage of using the absolute antenna PCV models in GEONET analysis. Noguchi et al. (2008) compared accuracy of results with the IGS models and with GSI’s original models and concluded GSI models should be applied for GEONET stations. Toyofuku et al. (2009) summarized evaluations about the antenna PCV models for GEONET.

Nishimura (2009) overviewed the GEONET system as well as InSAR and tilt/strainmeters in Japan from the viewpoint of monitoring crustal deformation.

Nishimura et al. (2010) developed a prototype to estimate an earthquake fault model using real-time 1-second sampling GEONET data. They concluded that it successfully estimated the fault models for the earthquakes with more than several centimeters of coseismic displacements at GPS stations. However, atmospheric disturbances often caused large noise levels in summer, which would make it difficult to detect coseismic displacements.

With the advent of multi Global Navigation Satellite Systems (GNSS) such as GLONASS, Galileo, and Quasi Zenith Satellite System (QZSS), a modernization of GEONET is required. Tsuji et al. (2009) sketched a plan to expand GEONET into GNSS Earth Observation Network System. Tsuji et al. (2010) reported future operational plans on GSI's geodetic continuous observation facility such as GEONET, tidal gauge stations and tilt/strain meters. Noguchi et al. (2010) focused on both advantages and disadvantages of switching current GPS antennas to GNSS antennas in monitoring crustal deformations. Tsuji et al. (2010) proposed to launch a 4-year R&D project to establish an integrated multi-GNSS data processing technique.

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### 3.3.2 Kinematic GPS and RTK

Sasahara et al. (2009) compared the accuracy of correction signal from MTSAT Satellite-based Augmentation System (MSAS) and Differential GPS (DGPS), and Precise Point Positioning (PPP) system with long base line KGPS positioning by Interferometric Translocation (IT) method composed by Colombo (1998).

Yokota et al. (2009) performed the source process inversion using 1-Hz GPS data only. The result shows fairly good agreement with a joint inversion of geodetic and strong motion data. The agreement demonstrates that 1-Hz GPS can infer the dynamic features of the rupture process even for an M6 class medium-sized earthquake.

Ohta et al. (2010) developed a low cost dual frequency GPS observation system consisting of a GPS receiver and a data logger. This system contains the function for RTK-GPS analysis, which is based on the RTCM ver. 3 format.

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### 3.3.3 GNSS Data Processing

Hatanaka et al. (2008) developed a GPS augmentation technique utilizing the L-band experimental channel of the Quasi-Zenith Satellite System (QZSS) for broadcasting augmentation parameters that are generated from the data of GEONET. The technique was designed for application to geodetic survey with a single-frequency GPS receiver. Ambiguity-fixed solutions were obtained for 56-100 per cent of the entire 15-minute-observation sessions in survey experiments.

Hatanaka (2008) developed a compression format for GNSS observation data that is compatible with RINEX ver. 3.00 format and tools. For data at sampling intervals of 30 seconds, the achieved compression ratio (defined as the ratio of the size of the compressed file relative to the size of the uncompressed file), combined with the additional text compression, is about 38 % of that by the simple application of text compression.

Munekane et al. (2008a) quantitatively evaluated, by numerical simulation with a satellite positioning system simulator (Munekane et al., 2008b), how the coming Quasi Zenith Satellite Systems (QZSS) could enhance GPS applicability in land survey in those areas where sky view was blocked. They obtained the following results: 1) QZSS observations considerably improve positioning accuracies at those sites where satellite visibilities are poor, 2) neglect of the tropospheric delay effects may result in large biases (up to 5 cm) of the estimated positions, especially in the vertical component, even for a short baseline, which are not mitigated even by adding QZSS observations, and 3) higher limit of the lowest elevation angle of observable satellites will be tolerable for given precision requirement on land survey when QZSS observations are available.

Munekane et al. (2008c) quantitatively estimated the spurious annual vertical deformations due to poor modeling of tropospheric delays over Japan, through a numerical simulation. They found that the amplitudes of the deformations increase toward the north, reaching up to 3 mm maximum at around N45º, whereas the phases are uniform throughout Japan with maximum spurious subsidence in the middle of February. Munekane and Boehm (2010) revealed that the amplitudes of the spurious annual vertical deformations would be greatly reduced (below 1 mm at most sites) by the use of the mapping functions derived from numerical weather models.

Munekane et al. (2010) investigated the effect of multipath on GPS-derived vertical coordinates of the GPS station, TSKB, in Tsukuba, Japan, and detected that the multipath was responsible for the large time-correlated errors with an amplitude greater than 1 cm.

Kobayashi (2007) investigated the repeatability of GPS 6-hour analysis. The spatial monitoring procedure was adopted to watch the 6-hour GPS coordinates.

Shoji et al. (2009) summarized the results of the Japanese GPS meteorology project “GPS/MET JAPAN” conducted from 1997 to 2002 and reviewed subsequent researches. In this project, precipitable water vapor derived from GEONET is fed to the data assimilation system in numerical weather predictions, which resulted in improvement of positioning accuracy of GPS.

Takagi et al. (2010) developed an improved analysis process of the GPS network around major active volcanoes based on JMA’s operational meso-scale numerical weather analysis (MANAL). This approach is convenient and effective for GPS observation at steep areas such as volcanoes.

Ohtani et al. (2010) introduced a new Continuous GPS Network of the Geological Survey of Japan, AIST.

Shimada (2010) compared the coordinate solutions with the PCV models of the absolute and the relative receiver antennas for the analysis of the dense regional GPS network in Japan with the fiducial sites in and around East Asia. In the conclusion, generally the solutions adopting the absolute PCV models gain better repeatability compared with those with the relative models, indicating the absolute PCV models are more precise than the relative PCV models.

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### 3.3.4 REGMOS

GSI has improved the remote GPS monitoring system for volcanoes. The communications control unit was remodeled in 2006 for reinforcement of communication function and became capable of four different kinds of communication including a wired circuit. Further remodeling was carried out in 2007 and 2008 to add a new function to switch communication terminals of the unit remotely.

After that the new system was developed in 2009 - 2010 which introduced the synthesized control unit suited to a high-speed satellite communication (communication service BGAN by Inmarsat). The synthesized control unit can watch the connection status and control electricity automatically. This new system has several features; high-speed data communication by TCP/IP, use of data logger for simultaneous data acquisition, and adoption of on-board GPS receiver for electric power saving. The shape of the system is an octagon with solar panels on all sides, which are expected to improve the charge efficiency in frigid conditions.

### 3.3.5 Tsunami Monitoring System

Kato et al. (2008) reported installation of a tsunami monitoring system using a GPS buoy off Muroto Peninsula, Japan. The GPS buoy successfully recorded the tsunami with about 10 cm amplitude. The simulated record has shown excellent consistency with the observed tsunami.

Offshore and coastal direct tsunami-wave profile observation system should be included in the tsunami monitoring system. Nagai et al. (2007) introduces basic design of the future tsunami monitoring system using newly developed GPS buoy system and other coastal and on-site sensors. Method of real-time tsunami data processing system is also introduced.

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## 3.4 SAR

JAXA has been operating the Advanced Land Observation Satellite (ALOS), also known as “Daichi”, since Jan. 24 2006. One of the three sensors installed is the L-band Synthetic Aperture Radar (SAR), PALSAR, and is being used for monitoring the earth surface frequently based on the systematic observation plan. L-band SAR has a unique function of providing a surface deformation map by means of the differential SAR interferometry for the two datasets separated by several tens of the days. PALSAR, a representative and unique L-band SAR operated in space, has been used for the detection of the surface deformation which occurred in 2010. The examples include:

1) 2010 Haiti earthquake
(http://www.eorc.jaxa.jp/ALOS/img_up/jdis_pal_haiti_100116.htm)
2) 2010 Chile Earthquake
(http://www.eorc.jaxa.jp/ALOS/img_up/jdis_pal_chile_eq2010_09.htm)
3) New Zealand Earthquake
(http://www.eorc.jaxa.jp/ALOS/img_up/jdis_pal_nzleq_100911.htm)
4) Volcanic eruption monitoring for Merapi
(http://www.eorc.jaxa.jp/ALOS/img_up/jdis_pal_merapi_oct2010_1.htm)

Shimada et al. (2008) gave a brief summary on the improved performance of the Japanese ALOS/PALSAR, an L-band synthetic aperture radar, and reported detection of crustal deformation signals at Hawaii. Related works are found in Miyagi et al. (2009), Myer et al. (2008), Sandwell et al. (2008), Shimada (2006; 2010), Shimada et al. (2010), and Tong et al. (2011).

GSI regularly performs SAR Interferometry (InSAR) analysis with PALSAR data obtained by ALOS. One of the purposes of the InSAR analysis is to monitor ground deformation associated with earthquake or volcanic activities, or due to subsidence or landslide. Interferograms obtained are regularly published and available to the public on the web site (http://vldb.gsi.go.jp/sokuchi/sar/index.html). InSAR can be a standard tool to monitor tectonic crustal deformation.

Amagai et al. (2007), Suzuki et al. (2007), and Amagai et al. (2008) made InSAR analyses for the data related to the 2007 Noto Hanto Earthquake, the 2007 Niigataken Chuetsu-oki Earthquake, and the 2008 Iwate-Miyagi Nairiku Earthquake, respectively. The results contributed to determination of the spatial extent of the damaged area and to estimation of the mechanisms of the earthquakes.

Tobita et al. (2009) carried out InSAR analysis for devastating earthquake disasters abroad and estimated fault models.

GSI detected subsidence on Tsugaru plains by InSAR, where leveling survey had never been carried out. GSI established a new leveling route in this area to monitor the subsidence more precisely. Morishita et al. (2010) showed that the vertical displacements obtained by InSAR analysis were in agreement with those from leveling.

Une et al. (2007) detected primary landslide associated with the 2007 Noto Hanto earthquake by InSAR. Suzuki et al. (2010) detected landslides near Mt. Gassan in Yamagata prefecture.

Nakamura et al. (2007a) calculated detailed seasonal variations in ice-flow for Shirase Glacier using the data obtained by Japanese Earth Resources Satellite-1 (JERS-1) synthetic aperture radar (SAR). Twelve pairs of images of 44-days repeat cycle from 30 April 1996 to 1 July 1998 were used to estimate ice-flow fields using an image correlation method. Nakamura et al. (2007b) applied an image correlation method to Japanese Earth Resources Satellite-1 synthetic aperture radar data obtained from 1996 to 1998 to examine flow velocity within Shirase Glacier, Antarctica. From the grounding line to the downstream region, the obtained ice-flow velocity was systematically higher on the western streamline than the eastern. Nakamura et al. (2010) studied temporal fluctuations in the flow velocity of Shirase Glacier in Antarctica using 15 synthetic aperture radar scenes obtained by the Japanese Earth Resources Satellite-1 (JERS-1) in 1996-1998 and 9 scenes obtained by the Advance Land Observing Satellite (ALOS) in 2007-2008.

Yamanokuchi et al. (2010) developed an interferometric synthetic aperture radar (InSAR) digital elevation model (DEM) with 50m grid spacing for the Breivika-Asuka Station area, East Dronning Maud Land, Antarctica with the aid of the elevation data measured by the Geoscience Laser Altimeter System (GLAS) as ground-truth data.

Ando and Okuyama (2010) discussed the possibility of deep roots of upper plate faults and earthquake generation using SAR.

Ozawa and Shimizu (2010) attempted to reduce atmospheric noise in InSAR using simulation from the 10km-mesh numerical weather model provided by Japan Meteorological Agency. A radar propagation path was estimated using the ray-tracing technique in order to consider atmospheric heterogeneity. The average of residual standard deviations for interferograms employed for reducing atmospheric noise was

13 mm, which is almost the same as those for interferograms employed for atmosphere-topography correction.

Hashimoto and Fukushima (2010) attempted to detect secular deformation associated with plate subduction using ALOS/PALSAR images and discussed several error sources in resulted interferograms. Hashimoto et al. (2010) reported coseismic and postseismic deformations of large to moderate earthquakes in 2008 and 2009 detected with ALOS/PALSAR, and their preliminary fault models.

Hobiger et al. (2010) illustrated the importance of ray-traced tropospheric corrections for InSAR data, using high-resolution numerical weather forecast model output.

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### 3.5 Other Techniques

Yamamoto (2007) discussed observation of crustal movement using volumetric and multi-component strainmeters in the Tokai region performed by The Japan Meteorological Agency. Tidal strain, atmospheric pressure effects, precipitation effects, and geomagnetic effects are removed from the observed data in real time. The corrected strain is monitored 24 hours a day. Yamamoto et al. (2008) evaluated detection levels in the time domain through the analysis of power spectra to investigate the detection limit of the volumetric strainmeter, the multi-component strainmeter and GPS in the Tokai and Kanto regions.

Katsumata et al. (2010) evaluated the detection level of crustal deformation of a 200 m baseline laser extensometer installed in Hamamatsu city in the Tokai region. They concluded that the laser extensometer would detect the crustal deformation due to the Tokai long-term slow-slip event earlier than the GPS network.

Araya et al. (2007) discussed observational results of a laser strainmeter and presented reviews of GPS measurements. A two-color laser interferometer is introduced and proposed as well. By combining these techniques, all based on quantum standards, a highly accurate and precise geodetic strain observation will be realized.

Araya et al. (2010) described a highly accurate and precise strain measurement system based on quantum standards, as well as its observational results of coseismic far-field crustal deformations. Analyses of the data impose a strong constraint on dislocation theories and determine fault parameters, particularly for the earthquakes in deep region.

Sakai et al. (2007a) applied the finite element method (FEM) to create numerical models of crustal deformation of a volcano. As the number of FE model becomes larger, the results of FE analysis approach Yamakawa’s solution, which demonstrates improvement of precision of calculation. However, the number of FE model should be lowest so far as the necessary precision of calculation is ensured. Mogi-Yamakawa’s model only holds good under the limited condition that a sufficiently small spherical pressure source exists at some depth within a semi-infinite homogeneous elastic body. Sakai et al. (2007b) developed numerical models with a large a/D ratio (a: radius of the sphere, D: depth of the sphere) based on the finite element method (FEM), and obtained numerical solutions of surface deformation.

Takagi et al. (2010) developed an improved atmospheric correction method in electro-optical distance measurement (EDM) based on JMA’s operational meso-scale analysis (MANAL). Applying this method to EDM data at Asamayama volcano, the seasonal fluctuation caused by inhomogeneity of refractive index in atmosphere was removed completely.

GSI started experimental measurements of leveling in a north-south route from Shizuoka to Omaezaki to evaluate the effects of thermal expansion on invar-made staffs caused by sunshine. In the north-south direction, the Sun shines on the northern-side staff facing south, but not on the southern side staff facing north, and thus produces differential changes in temperature between the two staffs, which result in differential thermal expansion between the two and affect the reading of leveling, that is, the reading of the northern-side staff becomes much smaller than that in the ideal condition of no thermal effects in comparison with the case of the southern-side staff. Because of the seasonal changes of the incident angle of sunshine at mid latitudes, the influence of sunshine should be larger in winter and the leveled height differences are apt to show apparent subsidence in winter toward the south, namely toward Omaezaki. Control experiments of leveling were made along the route; one case with normal invar staffs and the other with new super-invar staffs that have much smaller coefficient of thermal expansion. The results demonstrated that the amplitude of seasonal fluctuations in the leveled height difference was smaller in the case with new super-invar staffs than in the other case, which is consistent with the hypothesis that the cause of the annual variations observed in repetitive Omaezaki-area leveling surveys be the change of temperature on the staff surface. They will continue experimental observation, comparatively together with actual measurements of the surface temperature of staffs, to identify the causes of the annual variations.

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## 4. General Theory and Methodology

GSI published the Japan Geodetic Datum 2000 (JGD 2000) in April 2002. Because the published coordinates of the control points were based on the coordinates at 1997.0, the results of current surveys based on the control points are affected by the crustal deformation which has accumulated from the original epoch to the current epoch. In order to maintain the consistency between present GPS surveys and the geodetic datum, GSI has introduced semi-dynamic correction since January 2010.

Tobita et al. (2009) compared three equations for meridional distance from the equator and found that Bessel's simple equation was very easy for computer programming and has the fastest convergence and the highest calculation speed.

Tobita (2009) developed the coordinate revision software "PatchJGD" that can efficiently update the stations' geodetic values (latitude/longitude and X/Y in plane coordinate system) caused mainly by episodic crustal motions. The software was used for the 2007 Noto Hanto earthquake and four earthquakes.

Xu et al. (2007) proved that a fully unknown variance-covariance matrix is not estimable. They gave a new theorem on the estimability of a linear function of variance and covariance components and proposed a new method to estimate the variance-covariance matrix with special structure. Xu (2008) proposed using measured orbits as approximate values and derived the corresponding coordinate and velocity perturbations. Li et al. (2008) show that stochastic models of GPS data depend on elevation angles of satellites, the types of GPS data and the types of receivers. GPS data also show cross-correlation.

Xu (2009a) develop a GCV-based method to simultaneously determine both the weighting factors of geo-data and the regularization parameter. In addition, an unbiased estimator of the noise variance by correcting the biases of the regularized residuals was derived. Xu (2009b) proved that setting the initial values of partial derivatives to zero in the determination of gravity fields from satellite orbits is prohibited both mathematically and physically. It violates the physics of motion of celestial bodies. Xu (2010) provides a tutorial on mixed integer linear models for GPS/InSAR ambiguity resolution.

In estimating displacements and slip deficits from geodetic data in the inversion methods based on Bayesian models, one uses a matrix representing the spatial derivatives and applies Akaike Bayesian Information Criterion (ABIC) to optimize the weights of constraint conditions. Iinuma (2009) discussed the case where the matrix is rank deficient.

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## 5. Determination of the Gravity Field

### 5.1 Outline of Gravity Survey

GSI completed the third cycle of national gravity connection survey in 2009 using FG5 absolute gravimeters and relative gravimeters. The network of gravity survey consists of 30 fundamental gravity stations (FGSs) and 144 first-order gravity stations (GSs). In addition, GPS survey and leveling have also been carried out at those gravity stations to precisely determine their geodetic coordinates; to date the survey has been completed at 18 per cent of the network stations for GPS and 44 per cent for leveling.

GSI carried out absolute gravity measurements at 11 FGSs with FG5 absolute gravimeters (Micro-g LaCoste Inc.: Nos. 104, 201 and 203). During the period concerned, GSI established four new FGSs, Wakkanai in 2007, Ashizuri and Kushimoto in 2009, Hachinohe in 2010, and the total number of FGSs amounts to 30.

### 5.2 Absolute Gravimetry

To examine the possible change of gravity associated with the 2008 Niigata-ken Chuetsu earthquake, GSI made absolute gravity measurements at Nagaoka FGS in December 2008 and detected a gravity decrease of 7.3 microgals with respect to the value in May 2005.

Aiming at developing new techniques to monitor the groundwater variation by means of precise gravity measurements, Research Institute for Humanity and Nature (RIHN) introduced a field type absolute gravimeter, Micro-G LaCoste Inc. A10 (A10-017) in Dec. 2007. Since then, several test measurements in the field have been conducted not only to confirm the accuracy of the instrument but also to investigate the practical and efficient measurement methods for field surveys. Using A10-017, Nishijima et al. (2010) conducted the repeated gravity measurements at Takigami geothermal field from Feb. 2008 to Mar. 2010, and detected the gravity changes before and after the regular maintenance of the geothermal power plant.

The A10-017 is also employed for the gravity measurements in Jakarta, Indonesia to detect the gravity changes due to groundwater changes and associated land subsidence. Fukuda et al. (2010) discussed the possible applications of A10 in connection with its portability and accuracy in field surveys.

The Geological Survey of Japan (GSJ), National Institute of Advanced Industrial Science and Technology (AIST) carried out absolute gravity measurements for various purposes including (1) groundwater monitoring in Karasuyama area every year (Sugihara et al., 2009), (2) research and development about processing of nuclear waste in Horonobe area from 2008, (3) calibration of FG5 in Tsukuba mountain every year, and (4) calibration of superconducting gravity meter at Tsukuba University in 2007. GSJ also carried out the so-called hybrid gravity measurements at the Ogiri geothermal field twice in 2007 (Sugihara and Ishido, 2008).

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## 5.3 Gravimetry in Antarctica

As an activity of the 51st Japanese Antarctica Research Expedition, GSI conducted absolute gravity measurements with two FG5's (Nos. 203 and 104) at Syowa Station (IAGBN No.0417) and its backup site, nearly continuously for one month period from December 23, 2009 to January 31, 2010. The gravity values obtained at these two sites agree within 3 microgals with those obtained with the same meters in 2004, indicating absence of uplift of land.

Kim et al. (2010) made a validation study of six ocean tide models (CSR4.0, GOT99.2b, NAO.99b, FES2004, TPXO7.1, and TPXO7.2) using superconducting gravity data recorded at Syowa Station. From comparison with the observed loading effects, TPXO7.2 was found to be optimal among the six models.

Doi et al. (2010) calculated gravity changes induced by ice sheet mass changes from ice sheet elevation for 11 operation periods of the Ice, Cloud, and Land Elevation Satellite / The Geoscience Laser Altimeter System from 2003 through 2007. Calculated gravity changes were compared with gravity residuals from the superconducting gravimeter CT#043.

Prior to the discovery of the subglacial Lake Vostok, an Askania Gs-11 gravimeter was operated at Vostok Station, Antarctica in 1969 to observe tidal gravity variations. To better understand tidal dynamics of the lake, Doi et al. (2009a) reanalyzed the data from the gravimeter using a Bayesian Tidal Analysis Program Grouping method (BAYTAP-G).

Doi et al. (2009b) reported installation of a new superconducting gravimeter (SG) CT #043 at Syowa Station in April 2003 which replaced TT-70 #016. Before the removal of the TT-70 #016, parallel observation with the two SGs was conducted for about 6 month. Tidal parameters and gravity residuals from the two gravimeters showed good agreement.

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### 5.4 Non-tidal Gravity Changes

Since 1996, GSI and Earthquake Research Institute (ERI), The University of Tokyo, have cooperatively conducted repetitive absolute gravity measurements at Omaezaki FGS. The station is located in the area of the anticipated great Tokai earthquake epicenter and the measurements are expected to monitor the absolute gravity changes of geophysical origin. They made measurements 11 times during 2007 to 2010 and the results were reported to the Coordinating Committee for Earthquake Prediction, Japan.

#### 5.4.1 Gravity Changes Associated with Crustal Deformation and Seismic and Volcanic Activity

GSI started intensive gravity survey in the tectonically active regions by combination of absolute and relative measurement (hybrid gravity measurement) in 2010, which is to be repeated in every five years. In 2010 the first cycle of measurements was conducted in five areas, namely, Shionomisaki, Ashizuri, Hakodate, Hachinohe, and Sendai.

Earthquake Research Institute (ERI), The University of Tokyo and Disaster Prevention Research Institute (DPRI), Kyoto University have been carrying out continuous absolute gravity measurements since April 2008 at the Sakurajima volcano (Okubo et al., 2010). They presented technical tips for successful measurement from pieces of bitter experience during the period. Observational result clearly shows that significant (~10 microgal) gravity decrease occurred in July 2009 and in October 2009. These epochs correspond to the onset of active emission of volcanic ash (July 2009) from the Showa volcanic vent and to the explosion from the Minamidake crater in October 2009, suggesting the rise of the magma head in the conduits of the Sakurajima volcano brought about the significant gravity change.

Tanaka et al. (2007) developed a theoretical computation method for viscoelastic post-seismic deformation to include the effects of compressibility in a self-gravitating spherically symmetric earth model. This method is useful when interpreting large-scale surface deformation and gravity variation, caused by a large earthquake, which are observed by GPS and GRACE. Tanaka et al. (2009) developed a theoretical computation method for viscoelastic post-seismic deformation to include the effects of 3-D viscosity structure in a self-gravitating spherical earth model. The effects of heterogeneity in viscosity due to a plate subduction are estimated to compare with satellite gravity data. Tanaka et al. (2010) analyzed absolute and relative gravity data obtained in the Tokai area. It is shown that the observation result can be theoretically interpreted by a fluid migration through a fault fracture zone along the plate boundary caused by a slow slip.

Hayashi et al. (2007) analyzed sea surface height data obtained by satellite altimetry from Jason-1 and TOPEX/Poseidon to investigate a possible change of the geoid due to the 2004 Sumatra-Andaman earthquake. A slightly positive geoid change in the region between the trench and outer arc was identified.

Kusumoto et al. (2008) carried out precise gravity measurements at the benchmarks around the Omaezaki peninsula, Shizuoka, Japan. By comparing these gravity values with the values obtained in 1970, they found gravity changes caused by height changes of the Eurasian plate side due to subduction of the Philippine Sea plate.

Ukawa et al. (2010) reported calibration of three Scintrex CG-3M gravimeters. Calibration was performed three times (1999, 2003 and 2006) over eight years, and the obtained calibration factors shifted at rates of the order of 10 ppm/year for several years after manufacturing. The results were successfully applied to microgravity measurements at Iwo-tou.

Nawa et al. (2009) detected temporal gravity changes due to coseismic change and precipitation effect for the 2004 off the Kii peninsula earthquakes.

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### 5.4.2 Gravity Changes Associated with Hydrological Effects

In cooperation with National Astronomical Observatory of Japan (NAOJ) and Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kyoto University repeatedly conducted absolute gravity measurements in the Kamioka mine, where a superconducting gravimeter (SG) is operated. Seasonal gravity changes due to hydrological effects have been detected by both absolute gravity measurements and the SG observations (Higashi et al., 2009).

In cooperation with RIHN and other institutes, Kyoto University conducted the researches on the applicability of precise in-situ gravity measurements and GRACE observations for monitoring groundwater variations in urban areas.

Yamamoto et al. (2007) estimated mass variations in four major river basins of the Indochina Peninsula using the GRACE monthly gravity field solutions of UTCSR RL02 (University of Texas at Austin, Center for Space Research Release 02), JPL RL02 (Jet Propulsion Laboratory Release 02) and GFZ RL03 (GeoForschungsZentrum Potsdam Release 03). The estimated variations were compared with that calculated from a numerical model. Although the comparison over the combined area of the four river basins showed fairly good agreement, the phases were delayed by about 1 month compared with the model. The phase differences are probably due to improper treatments of the groundwater storage process in the hydrological model, suggesting that the GRACE data possibly provide constraints to the model parameters.

For the future improvement of JRA-JCDAS LDA and GRiveT Terrestrial Water Storage (JLG) model, Yamamoto et al. (2008) compared the annual phases and amplitudes of mass variations of GRACE and JLG model for 70 major river basins in the world. The annual phases of GRACE and JLG model showed good correspondence in most of the river basins, but about 1 to 2 month discrepancies were shown in Lena, Changjiang, Mackenzie, Orinoco, Yukon and Kolyma basins. They showed that the phases of the model can be improved using the GRACE result as constraints, because GRACE data represent actual mass variations of terrestrial water storage including groundwater.

Hasegawa et al. (2008) detected terrestrial water storage changes induced by the 2006 Australian drought from GRACE satellite gravity data. GRACE data showed unusual surface mass depression at south-east Australia in 2006 where historic rainfall deficiency was reported. They compared the GRACE data with those of hydrological models: the Global Land Data Assimilation System (GLDAS) and the JRA-JCDAS LDA and GRiveT Terrestrial Water Storage (JLG) models. Although the hydrological models indicated terrestrial water decrease in 2006, the magnitude was much smaller than the GRACE estimation. This suggests that the hydrological models may not properly recover the landwater storage changes caused by the drought.

Fukuda et al. (2009) reevaluated the water mass variations in four major river basins of the Indochina Peninsula using the newly released GRACE data. The estimated variations were compared with Soil–Vegetation–Atmosphere Transfer Scheme (SVATS) models with river flow models. The results showed that the groundwater and the river velocity played an important role in estimating the variation of total terrestrial storage. While in-situ gravity data directly reflect the local groundwater mass variations, the GRACE data can be used to determine regional or global scale variations which need to be determined precisely in order to discriminate the phenomena caused by human activities. They argue that hydrological models are necessary to link the regional/global scale and the urban scale variations.

Kazama and Okubo (2009) developed a new scheme to correct for hydrological gravity disturbances. They begin with solving nonlinear hydrological diffusion equations for groundwater distribution around the gravity observation point. Its spatial integration enables them to estimate the gravity change originating from groundwater. They applied the method to the gravity record at Asama Volcano in Central Japan during the rainy season in 2006 to find that their hydrological model reproduced the rapid increase and subsequent gradual decrease in gravity following rainfall events. The water mass within 150 m of the gravimeter is shown to dominate the observed gravity change during precipitation. It is also demonstrated that the use of adequately representative soil parameters is essential in order to accurately estimate the groundwater distributions and consequent gravity variations.

Nawa et al. (2008) reported temporal gravity changes due to precipitation associated with a typhoon at the Asama Volcano Observatory.

Tanaka (2010) described the gPhone gravimeter (serial number 90) which is based upon the LaCoste G-type gravimeter, tentative data recorded under an unideal condition, and then a future application plan for gravimetrical correction of groundwater change.

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### 5.4.3 Gravity Changes Associated with Sea Level Variation

Nawa et al. (2007a) studied the gravity change due to sea level changes caused by the 2004 Sumatra earthquake observed at Syowa Station, Antarctica. Nawa et al. (2007b) investigated the gravity change due to the 2004 Indian Ocean tsunami at Syowa Station, Antarctica.

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## 5.5 Gravity Survey in Japan

### 5.5.1 General

The Geological Survey of Japan (GSJ), National Institute of Advanced Industrial Science and

Technology (AIST) conducted gravity surveys in order to prove the brief feature of gravity anomalies in Japan. GSJ published eight detailed complete Bouguer anomaly maps of 1:200,000 scale, “Gravity Map Series” for Hiroshima District, Matsuyama District, Okayama District, and Kochi District as part of the gravity mapping program of Japanese Islands (Geological Survey of Japan, AIST, 2007; 2008; 2009; 2010).

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### 5.5.2 Hokkaido Area

The GSJ conducted gravity surveys of Usu volcano in 2009, and published maps and data (Geological Survey of Japan, AIST, 2010).

Geological Survey of Hokkaido (GSH) performed gravity surveys around Northern Rumoi region, Northwestern Hokkaido. In order to study the relationship between the gravity anomaly field and the hypocenter of the inland earthquake, they conducted a regional survey at 276 stations. Tamura et al. (2010) produced a regional Bouguer anomaly map, and also calculated terrain density distribution in this area.

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### 5.5.3 Honshu Area

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ) carried out the gravity survey in the Kofu basin from 2005 to 2008 for investigation of underground structure and active faults, and the gravito-metric map was published (Komazawa, 2010).

Okajima et al. (2009) studied the subsurface structures around the Osore-zan volcano, northernmost Honshu island, Japan by analyzing the existing gravity data over a 100 × 100 km square area. Based on the Fourier spectral analysis techniques, the Bouguer anomaly distribution is separated into 4 gravity components: (1) trend, (2) long wavelength, (3) short wavelength, and (4) noise. These gravity components are critically evaluated with other geological evidences. Particularly, each of the long and short wavelength components corresponds mainly to the horst-graben structure of granitic bedrocks and the undulation of the shallower accretion bedrocks, respectively. These facts demonstrate the usefulness of the filtering techniques.

Honda et al. (2008) constructed a detailed gravity anomaly map over the Noto peninsula. Four block boundaries which are identified by morphological/geological studies are recognized on the gravity anomaly map. Based on the relationships among the gravity anomalies, the geologic structures, the aftershock distribution and the source fault, it is concluded that the rupture size of the earthquake was constrained by the block structure in this region.

Tanaka et al. (2010) estimates the basement structure around the Tegano fault by gravity survey. The inferred schematic profile of the fault is consistent with a preexisting theory of the evolution of a reverse fault; this supports the hypothesis that the Tegano fault was derived from the deep part of the Byobusan fault which runs side by side with the Tegano fault.

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### 5.5.4 Shikoku and Kyushu Area

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ) carried out the gravity survey and published a Bouguer gravity anomaly map in Kagoshima District, Kyushu, Japan (Murata et al., 2007).

Laboratory of Geothermics, Kyushu University has carried out repeated gravity measurements using CG-3 and CG-3M gravimeters for 20 years in Fukuoka city and other places in the Kyushu Area. Saibi et al. (2008) applied integrated gradient interpretation techniques, such as horizontal gradient, tilt derivative and Euler deconvolution. With these techniques, they detected many faults and discussed the relationship between underground structure and low temperature geothermal systems. Fujimitsu et al. (2009) studied the area in Oto town, Fukuoka prefecture, in order to estimate the underground structure for the future hot spring well, and estimated Tagawa fault from the gravity survey at the northern to middle part of the town. Fujimitsu and Nishijima (2010) discussed the relation between the underground structure estimated by the gravity survey and non-volcanic hydrothermal systems at the southeastern part of Fukuoka city and Oto town. Nishijima et al. (2010a) measured gravity at 1947 points in order to detect an active fault (Kego fault) and to investigate its underground structure. Ehara and Nishijima (2010) studied the area around Hatchobaru geothermal power plant, and discussed the importance of geothermal reservoir monitoring in order to keep the sustainable geothermal development.

Nishijima et al. (2010b) used an A10 absolute gravimeter in 2008 to make gravity measurements around Takigami geothermal power plant, and detected a gravity decrease (about –20 microgal) caused by the maintenance of the geothermal power plant.

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### 5.6 Gravity Survey in Foreign Countries

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology

(GSJ) carried out a gravity survey at the Guinsaugon landslide along the Philippine Fault Zone in 2007 (Makino et al., 2007).

Laboratory of Geothermics, Kyushu University, has carried out gravity survey at geothermal areas in foreign countries. Setyawan et al. (2009) estimated the body structure of Ungaran volcano, Indonesia, using 2D forward modeling. The horizontal gradient analysis indicates that geothermal features at Ungaran volcano are structurally controlled and are located within the younger volcano. Sofyan et al. (2010) studied the gravity data acquired at Kamojang geothermal power plant. They compared the data with the gravity data previously obtained by University of Indonesia, and detected gravity decrease (–238 microgals) at the production area and gravity increase (143 microgals) in reinjection area from 2005 to 2008. Zaher et al. (2010) measured gravity at 160 points around Hammam Faraun hot spring, Sinai Peninsula, Egypt, using Scintrex CG-3 gravimeter in order to clarify the underground structure of hot spring. They estimated underground structure using 2D forward modeling method and interpreted the hydrothermal systems using gravity and magnetotelluric data.

Sun et al. (2009) studied the tectonics of the Tibetan Plateau where the Indian and Eurasian plates have been colliding for the last several tens million years. They present geodetic evidence of mass loss beneath the Tibetan Plateau and increasing crust thickness. Combined absolute gravity and Global Positional System (GPS) measurements at three stations in southern and southeastern Tibet during two decades reveal uplifting of the Tibetan Plateau at a millimeter-per-year level, but its underlying mass is diminishing, indicating that the crustal thickness is increasing at an annual millimeter to decimeter level.

Sun et al. (2010) reported a new absolute gravity (AG) network established in Southeast Alaska (SE-AK). Measurements were carried out during 2006–2008. The gravity in SE-AK is decreasing with a rate of −3.5 to −5.6 microgal/year. A bias of −13.2 ± 0.1 mGal exists between the Potsdam system and the AG data.

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### 5.7 Marine Gravimetry

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ) has been conducting marine gravity surveys since 1974 as a part of the geological mapping program of continental margin around the Japanese Islands. The survey vessel Hakurei-maru No.2 has been used since 2000. The cruises during the period from 2007 through 2010 are listed in Table 1. The gravity measurements were conducted using the same straight-line sea gravimeter, LaCoste& Romberg SL-2, in all the cruises. Free-air and Bouguer anomaly maps were published as appendices of "Marine Geology Map Series" at a scale of 1:200,000 (Geological Survey of Japan, 2007a; 2007b; 2007c; 2008a; 2008b).

Table 1. Cruises for marine gravimetry by the GSJ during the period from 2007 to 2010.

| Cruise ID | Cruise Period | Survey Area |
|---|---|---|
| GH07 | Jun. – Jul. 2007 | East of Tohoku District |
| GH08 | Jul. – Aug. 2008 | East of Okinawa Islands |
| GH09 | Jul. – Aug. 2009 | Northwest of Okinawa Islands |
| GH10 | Oct. – Nov. 2010 | Southwest of Okinawa Islands |

GSJ carried out sea bottom gravity surveys in the northern coastal zone of Noto peninsula in 2008 (Geological Survey of Japan, 2010) and in the offshore zone of Fukuoka prefecture.

JHOD carried out marine gravity surveys using three survey vessels "Shoyo" (3128 gross tons), and "Meiyo" (550 gross tons) during the period of FY 2006 to FY2010. These vessels are equipped with the sea gravimeter Bodenseewerk KSS-31 or KSS-30. The cruises from April 2007 to Dec. 2010 are listed in Tables 2 and 3 (Hydrographic and Oceanographic Department, 2009).

Table 2. Cruises of "Shoyo" for marine gravity surveys conducted by JHOD during the period from April 2007 to Dec. 2010.

| Cruise Period | Survey Area |
|---|---|
| Feb. – Mar. 2010 | Kaikata Kaizan |
| Oct. – Nov. 2010 | Nishinoshima |

Table 3. Cruises of "Meiyo" for marine gravity surveys conducted by JHOD during the period from April 2007 to Dec. 2010.

| Cruise Period | Survey Area |
|---|---|
| May – Jun. 2007 | Offing of Wakasa-wan |
| Aug. 2007 | Kikai caldera |
| Jun. – Jul. 2008 | Kikai caldera |

Hydrographic and Oceanographic Department (2009) reported gravity surveys at sea. The results of three cruises, northeast offing of Izu-Oshima, offing of Wakasa Wan and Kikai-Caldera surveyed in 2006-2008 are reported.

Fujiwara et al. (2009) studied geophysical characteristics and numerical modeling based on physical property data obtained in 2004-2007 marine cruise data. This is a kind of a basic study for international drilling proposal site survey.

Fujimoto et al. (2009) remodeled an ocean bottom gravimeter and carried out seafloor gravimetry in a limited area for seamless gravity mapping on land and seafloor.

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### 5.8 Data Handling and Gravity/Geoid Maps

Kuroishi et al. (2007a; 2007b) worked with GRACE data for recovery of the gravity anomaly field at medium wavelength locally over Japan. Monthly mean gravity anomaly blocks of 4 by 4 arc-degrees estimated from GRACE range-rate data exhibit rather large fluctuations probably due to aliasing, but the annual average model of the monthly blocks for 2005 shows distribution of only minor residuals with respect to a reference global geopotential model, GGM02C: ranges from – 35 to + 22 microgal, corresponding to geoidal undulations of – 3.3 to + 3.4 mm.

Kuroishi (2009) constructed a highly improved gravimetric geoid model, JGEOID2008, on a 1 by 1.5 arc-minute grid by combining surface gravity measurements and an altimetry-derived marine gravity model, KMS2002, with a GRACE-derived global geopotential model, GGM02C. A semidiscrete two-dimensional wavelet analysis/reconstruction method was employed in the combination for selecting the spatial wavelet signals of the highest quality out of the respective data sets. Intercomparison with GPS/leveling geoidal undulations over the four main islands of Japan reveals substantial improvement of JGEOID2008 over the previous model, JGEOID2004: the planar trend was reduced from 0.35 ppm to 0.18 ppm and the RMS of postfit residuals from 9.2 cm to 6.0 cm. Deviations of the mean sea surface heights at tidal stations on isolated islands above the reference ellipsoid from JGEOID2008, which provide local mean sea surface dynamic topography (SSDT), show good agreement with SSDT features estimated from oceanographic observation, indicating that JGEOID2008 has an accuracy within 10 cm. Kuroishi (2010) compared JGEOID2008 with the latest high-resolution global geopotential model, EGM2008, and demonstrated that JGEOID2008 is slightly superior to EGM2008 over Japan in terms of fit to GPS/leveling geoidal undulations.

JHOD carried out geophysical surveys (bathymetry, gravity and geomagnetics) on Kikai Caldera submarine volcano during 2006 to 2008. From the analysis on Bouguer gravity anomalies on the assumed density values of 1950 kg $m^{-3}$, Onodera et al. (2010) obtained a map of gravity basement depth of the caldera.

Ishihara and Koda (2007) estimated the thickness of the crust of the Philippine Sea using the sea gravity data collected by Hydrographic and Oceanographic Department and JOGMEC. Oikawa and Kaneda (2007) complied Japanese continental shelf survey to create a Bouguer gravity anomaly map in the northwestern Pacific Ocean. The anomaly map with a terrain correction with a radius of 30 km will contribute to further interpretation of submarine topographic features around Japan. Ueda et al. (2008) investigated crustal structure and calculated geophysical parameters (volume, density, magnetization） of 85 sea mounts, using the topographic depth soundings, free-air gravity anomalies, magnetic anomalies and Bouguer gravity anomalies on the assumed density values of 2,300 kg $m^{-3}$ and 2,700 kg $m^{-3}$. Sawada et al. (2009) corrected the errors in gravity anomalies originating from gravimeters and positioning systems, and made marine gravity datasets around Japan without noticeable inconsistency.

Sasahara et al. (2007) described the method of calculating the geostrophic current based on the Marine Geoid model and the altimeter sea surface height. Sasahara and Tanaka (2009) compared the geostrophic current, which was calculated with global gravity potential model "EGM2008" and altimeter sea surface height, with the ADCP current data, to estimate the accuracy of "EGM2008".

Sasahara et al. (2008) revised the geoid model "MGM2008" by using the gravity data derived from altimeter, and evaluated the difference between SSDHgeo (by altimeter and the geoid height) and SSDHctd (by CTD). The difference showed a small standard deviation. (SSDH = Sea Surface Dynamic Height)

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### 5.9 Theoretical Studies on Geoid and Gravity Field

The emergence of different types of satellite gravity missions and the requirement of accurate geoid information at high resolution have necessitated us to combine different kinds of gravity-related observables obtained from the Earth’s surface to satellite altitudes for geoid determination. Since those data are inevitably sensitive to the gravity field signals at different scales with their inherent error characteristics, Panet et al. (2009; 2010; 2011) worked on methodological development based on spherical wavelets in a domain decomposition approach. The resulting method can handle large data sets efficiently in terms of computation loads and combine a variety of gravity-related observables in a flexible manner in both scale and location domain. Application study to a GRACE-derived global geopotential model and surface gravity data over Japan showed the effectiveness of the method at an improved spatial resolution of about 15 km on the Earth’s surface.

Nozaki (2007) reviewed the Bouguer anomaly in the geophysical and geodetic context of gravity anomaly from a standpoint of studying subsurface density structures. The main purpose is to remove the intrinsic defects involved in the current definition of the Bouguer anomaly, such as the residual centrifugal acceleration due to the Earth’s rotation. Starting from the classical concept of the Bouguer anomaly, a new approach to the free-air anomaly has been shown based on the newly introduced concept of ‘station level $\rho_B$-free Bouguer anomaly’ that is based on the notion of the generalized Bouguer anomaly proposed by Nozaki (2006).

Sun et al. (2007) presented a new theory for calculating co-seismic strain caused by four independent types of seismic source in a spherically symmetric, non-rotating, perfectly elastic, and isotropic (SNREI) Earth model. Expressions are derived by introducing strain Green’s functions. A proper combination of these expressions is useful to calculate co-seismic strain components resulting from an arbitrary seismic source at any position in the Earth. Numerical computations are performed for four independent sources at a depth of 32 km inside the 1066A Earth model. Results in the near field agree well with that calculated for a half-space Earth model. A case study is performed and Earth model effects are investigated. Furthermore, the effects of spherical curvature and the stratified structure of the Earth in computing co-seismic strain changes are also investigated using the present dislocation theory and Okada’s (1985) formulation. Curvature effects are small for shallow seismic events, but they are larger for greater source depths. Effects of stratification are very large for any depth and epicentral distance, reaching a discrepancy greater than 30% almost everywhere.

Fu and Sun (2007) developed the theory of Molodenskiy (1977; 1980) on tidal gravimetric factors for a lateral inhomogeneous earth by considering density heterogeneity as well. Their numerical results show that the effects of density are of the same level as those of seismic waves: they are not negligible. The effects of the lateral inhomogeneous structure calculated for the real three-dimensional inhomogeneous model are much less, by a factor of about 0.2, than those of the simple Ocean-Land model presented in Molodenskiy and Kramer (1980). Collecting contributions from the seismic wave and density models, they obtain the completed total effect of the real three-dimensional inhomogeneous Earth structure on semidiurnal gravimetric factors, with a magnitude of about −0.16 to 0.1 %. This result is less than, but almost of the same order as that of Earth's elliptical effect (ca. 0.7 %; Dehant, 1995). Finally, they calculate the corresponding effects on tidal gravity for all three kinds of Earth tide: semidiurnal, diurnal, and long period ones. Compared to the tidal gravity changes, the gravity variations caused by the increments are about 0.15 % for the semidiurnal tide and 0.1 % for the diurnal and long period tides.

Fu and Sun (2008a) calculated the theoretical horizontal displacement field caused by the 2004 Sumatra earthquake in the Sichuan-Yunnan area according to the spherical dislocation theory. The results show that the theoretical value of displacement field is basically consistent with the observed value in situ with GPS. On this basis, they have calculated the co-seismic displacement field, strain field, changes of gravity and geoid of the whole Earth and China mainland and vicinity caused by the Sumatra earthquake.

Fu and Sun (2008b) formulated surface gravity changes caused by dislocations within a 3-D heterogeneous earth. This new theory is described using six independent dislocations: a vertical strike-slip, two vertical dip-slips perpendicular to each other, and three tensile openings on three perpendicular planes. A combination of the six independent dislocations is useful to compute coseismic gravity changes resulting from an arbitrary seismic source at an arbitrary position. Based on the 3-D lateral inhomogeneous P-wave velocity model, Fu and Sun (2008) deduce the 3-D density and S-wave velocity models using the relation of Karato. Finally, numerical computations are performed for a location south of Japan (30°N, 135°E). They calculate the coseismic gravity changes resulting from the six independent dislocations for source depths of 100, 300 and 637 km, respectively. Numerical results show that the maximum 3-D effect varies concomitantly with the dislocation type and the source depth. For seismic problems, the effect of elastic parameter $\mu$ is found to be dominant.

Sun et al. (2009) summarized and reformulated co-seismic deformations for a spherical symmetric earth model, presenting unified expressions to accommodate physical deformations: displacement, potential, gravity, geoid and strain changes. The corresponding Green's functions are derived by combining spheroidal and toroidal deformations. Sign errors in previous publications are corrected in these new formulas. These expressions are developed basically for a deformed earth surface because most traditional geodetic measurements are performed on the terrain surface. However, through development of space geodetic techniques, such as the satellite gravity missions, co-seismic gravity changes can be detected from space. In this case, the above dislocation theory (e.g. the co-seismic gravity change) cannot be applied directly to the observed data because the data do not include surface crustal deformation (the free air gravity change). Correspondingly, the contribution by the vertical displacement part must be removed from the traditional expressions. For this purpose, the authors present the corresponding expressions applicable to space observations. Global co-seismic deformations caused by the 2004 Sumatra–Andaman earthquake (M9.3) are studied as an application of the new Green's function. That earthquake caused a global deformation detected by GPS, strainmeters and even a satellite gravity mission. These global deformations are calculated based on the derived Green's functions and the seismic-wave derived earth model. A segment-summation scheme is used considering the slip distribution on a limited fault plane. The results are useful for interpreting observed deformations, especially those in the far field. The earthquake reveals global co-seismic deformations and effects of spherical curvature and the earth's layered structure. Comparisons between results for a spherical earth model and a half-space model show a large discrepancy at an epicentral distance of about 1000 km, implying that effects of spherical curvature and layer structure are considerably large. In addition, the theoretical results are compared with the real observed strain steps, horizontal displacements and gravity changes caused by that earthquake. Good agreement validates the results of the current theoretical work. They also discuss the application of the above theory to the GRACE data through several case studies.

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## 5.10 Space Gravimetry

### 5.10.1 Lunar and Planetary Gravimetry

Prior to the launch of SELENE, Goossens and Matsumoto (2007) developed a degree and order 75 spherical harmonics lunar gravity field model from 3 months of Lunar Prospector tracking data, and showed that despite relatively large differences in gravity anomalies over the far side due to differences in processing the data, models perform similar in terms of orbit determination. They also showed through covariance analysis that SELENE is expected to contribute up to degree 50, with an expected one order of magnitude improvement for degrees up to 30. Goossens et al. (2009) presented results for orbit determination of the three satellites of SELENE, and evaluated orbit accuracy for the main satellite to be about 50 m by using altimeter crossovers and orbit overlaps. They revealed that the orbit accuracy for the sub-satellites Rstar and Vstar is restricted due to sparse data coverage, but the inclusion of differential VLBI data greatly improves the consistency of the orbits down to a level of 10 m.

Iwata et al. (2009; 2010) reviewed the mission instruments for lunar gravimetry onboard the SELENE sub-satellites Rstar and Vstar, and evaluated the properties of satellite bus, the mission instruments, and observation system including ground stations during initial checkout phase. They showed that the on-orbit properties of the measurement systems had adequate performance for the planned gravity recovery mission. Tsuruta et al. (2009) presented a detailed analysis of the status of the sub-satellites using the telemetry data. Asari et al. (2009) proposed a new method to know the status of phase lock loop during SELENE 4-way Doppler measurement when the main satellite is on the far side and real-time telemetry is not available. The proposed method was validated during the real operation and contributed to retrieve far-side gravity information.

Ogawa et al. (2009) reviewed the SELENE ground system in terms of the flight dynamics operation such as orbit determination, orbit prediction and orbit maneuver planning, and described how the orbital data are distributed through mission operation and analyses system. Ishikawa et al. (2009) described the stream of the selenodetic data from the SELENE satellites including altimeter data, Doppler, range, and VLBI satellite tracking data in association with computer systems at SELENE Operation and Analyses Center (SOAC), National Astronomical Observatory of Japan (NAOJ), and VLBI stations.

Matsumoto et al. (2008) reported pre-launch simulation results for SELENE gravity mission and showed the expected impact of 4-way Doppler and VLBI tracking data on lunar gravity field modeling. Yan et al. (2008) showed potential improvements in lunar gravity field model by simultaneous tracking of SELENE and Chang'E-1 satellites using differential VLBI. Goossens and Matsumoto (2008) re-evaluated 2nd-degree lunar potential Love number $k_2$ using pre-SELENE satellite tracking data. They obtained the satellite-derived $k_2$ value which is in closer agreement with Lunar-Laser-Ranging-derived value than previous determination. Goossens (2010) applied spectral leakage corrections to the inverse problem of determining the gravity field of a planetary body expressed in a truncated expansion of a complete and infinite set of basis functions. He showed that the leakage corrections lead to solutions with less spurious power in the higher degrees, and solutions that are generally closer to their true values, when compared to standard least-squares solutions.

A series of SELENE gravity models were presented and associated tracking data analyses were described as more data were accumulated. Namiki et al. (2009c) presented SGM90d model which was a spherical harmonic solution to degree and order 90, and was developed from 5 months of SELENE Doppler and range tracking data and those of historical lunar satellites. Owing to the 4-way Doppler data which for the first time provided the far-side tracking data coverage, they revealed ring-shaped far-side gravity anomalies and discussed different compensation states between the near-side and the far-side. Matsumoto et al. (2009) derived SGM90f model with the same amount of data as Namiki et al. (2009c), but used longer arc length for one of the sub-satellites called Rstar to improve low-degree gravity coefficients. Goossens et al. (2008) presented a lunar gravity field model derived from 8 months of SELENE tracking data. Matsumoto et al. (2010) and Kikuchi et al. (2010) presented a 100 × 100 model SGM100h which incorporates 14.2 months of SELENE tracking data including all the 4-way Doppler data obtained during the life time of the relay satellite Rstar. They showed that SGM100h gave the highest correlation with topography as high as 0.9 through degree 70. Goossens et al. (2010) further incorporated S-band same-beam differential VLBI data between two sub-satellites (Rstar and Vstar) to derive SGM100i model. It is confirmed that SGM100i gave better orbit consistency than previous gravity models did.

On the basis of the gravity and topography models of the Moon developed by SELENE, Namiki et al. (2009a; 2009b; 2010) proposed new classification and compensation mechanism of lunar impact basins. Impact basins on the lunar far-side are classified into Type I and Type II basins depending on the magnitude of central gravity high in free-air and Bouguer gravity anomalies. Ishihara et al. (2009; 2010) computed a map of lunar crustal thickness based on SELENE gravity and topography models. They found that the differences between Type I and Type II basins are controlled by the ratio between pre-impact crustal thickness and impact scale. Sasaki et al. (2010) used the SELENE-derived gravity and topography models to discuss the elliptical shape of the South Pole-Aitken Basin.

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### 5.10.2 Satellite Gravity Missions

In order to see global and Southern Ocean mass variations, Kuo et al. (2008) compared three data sets of (1) GRACE-observed ocean bottom pressure (OBP), (2) steric-corrected satellite altimetry (ENVISAT) and, (3) the Estimating the Circulation and Climate of the Ocean (ECCO) model OBP data. They found larger discrepancies among the data sets for the Southern Ocean. Although there are still some errors in GRACE and altimetric observations, the study implies that GRACE and altimetry data could potentially provide an improved constraint on steric sea level and ocean mass variations in the Southern Ocean.

Aiming at the regional gravity field modeling using GOCE gravity gradient tensor, Janák et al. (2009) derived a spatial integral form in the geocentric spherical coordinates. All of the second partial derivatives of the generalized Stokes' kernel are derived, and six surface Fredholm integral equations are formulated and discretized.

In cooperation with NIPR (National Institute of Polar Research), Kyoto University conducted GRACE data analyses to recover the mass changes in Antarctica. Using monthly solutions of GRACE data, Ice Cloud and land Elevation Satellite (ICESat) data and the in-situ snow-stake data, Yamamoto et al. (2008) discussed the cause of the positive mass trend in Enderby Land, East Antarctica. They conclude that the bulk of the GRACE mass trend can be explained by snow accumulation and basal ice-sheet outflow.

Using GRACE monthly gravity data before and after the 2004 Sumatra-Andaman earthquake, Ogawa and Heki (2007) detected postseismic gravity (geoid height) change for the first time in the world, and attributed it to the movement of supercritical water at depth. Heki and Matsuo (2010) found sudden decrease of ~5 microgals in the GRACE data on the backarc side of the epicentral region of the 2010 Chilean earthquake. Appropriate fault parameters and a model based on the spherical stratified earth successfully reproduced the observed coseismic gravity changes. This is the second example of mapping coseismic gravity changes using satellite gravimetry.

Polarities of ENSO index are considered to govern precipitation anomalies in equatorial Africa and South America. Morishita and Heki (2008) found correlation between monthly gravity values from GRACE, possibly reflecting soil moisture variations, and recent changes in ENSO index in 2005-2007.

Matsuo and Heki (2010) investigated GRACE monthly gravity data set and found that 40-50 gigatons of mountain glaciers are lost from the Himalayas and major mountain belts in central Asia. Fairly large uncertainty comes from possible contribution from glacial isostatic rebound, separability from groundwater loss in northern India, and climate fluctuations in decadal timescales.

Terms proportional to squares of time (quadratic changes) are often significant in time-variable gravity fields recovered by GRACE. Ogawa et al. (2011) found that linearly changing components of precipitation are largely responsible for such changes.

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### 5.11 Superconducting Gravimetry

Doi et al. (2010) studied the effect of liquid helium level on the position of the proof mass of superconducting gravimeter (SG). The effects on three different types of SGs were calculated by approximating the geometry between the SG sensor unit and liquid helium reservoir using a double-layered cylinder model.

It has been known that the superconducting gravimeter has intrinsic instrumental noise at around 100 second period. Imanishi (2009) identified another parasitic mode for superconducting gravimeters, and discussed the cause of these instrumental noise.

Imanishi et al. (2009) analyzed records from superconducting gravimeters to investigate coseismic gravity changes caused by two earthquakes. Although plausible signals were detected in some cases, the result indicated the difficulty in identification of the coseismic signals caused by inland earthquakes with shorter epicentral distances to gravity stations.

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### 5.12 Air-borne Gravimetry

Since there are few scientists in Japan who are engaged in air-borne gravimetry, it has been conducted mostly by Segawa group belonging to the Tokyo University of Marine Science and Technology (TUMST). The air-borne gravimeter used is FGA-1 SEGAWA Model developed in 1998 by J. Segawa with the aid of Tokyo Keiki Incorporated, Japan. It is right to say that gravity has been well measured in most part of the Japanese Islands. However, there still remain lots of zones void of gravity data at important areas such as the coastal lines and mountainous areas.

The Segawa group considers that most important mission of gravity measurement in Japan, from the new point of view, is to clearly find the distribution of local gravity anomalies so as to delineate active seismic faults along and/or across the Japanese Islands. Their air-borne gravity measurements are made mainly on board helicopters focused at seismic zones which neighbor often the atomic electric plants. They undertook measurements at more than 12 sites for the last 10 years: The sites cover coastal zones at Ibaraki Pref., the Suruga Bay, the Enshunada Deep, Kozu and Miyake Islands, Sata Peninsula, Shikoku, Noto Peninsula, the Wakasa Bay, the Seto Inland Sea, and Shimokita Peninsula. Recent summary of their helicopter gravity measurements was reviewed by Segawa (2010). The work regarding traceability of known active fault on land over to the sea floor was made public by Segawa (2009). The detailed air-borne gravity measurements in the north Noto Peninsula was carried out in 2008 and it is reported by Komazawa et al (2010).

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## 5.13 Geomagnetic and Ionospheric Researches

GSI conducted 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 30 stations distributed in the country during 2007-2010. The observation data are published 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.

Ji et al. (2007) reported a spatial model of geomagnetic filed of Japan for epoch 2000, which was obtained by applying the spherical cap harmonic analysis to the observed data from magnetic observatories, the continuous geomagnetic stations and the first-order geomagnetic stations in Japan.

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## 6. Crustal Deformation

Heki (2007) reviewed crustal movements in the Japanese Islands observed with the dense GPS array GEONET, and categorized them by temporal changes, i.e. secular, transient and seasonal crustal movements.

Yamaguchi et al. (2010) developed crustal deformation database for strain- and tilt-meters. It continuously receives telemetering data via internet protocol all over the Japan in real-time and data are stored at the database server. Users can easily make basic operations, e.g. drawing, filtering, tidal analysis, and downloading data, through a WWW-based graphical interface.

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## 6.1 Secular Movements

### 6.1.1 Plate Motion

Sato et al. (2009) re-estimated the velocity of Simosato from LAGEOS SLR data for 15 years. A velocity of 2.9 cm/year in the direction to 294$^{o}$N with respect to the Eurasian plate was obtained. This is close to the subduction velocity of the Philippine Sea plate, indicating the strong interplate coupling at this region.

Saito et al. (2008) reported the result of seafloor geodetic observation at Sagami Bay. The result shows a crustal movement velocity of 4.1 cm/year toward NW with respect to the stable part of the Eurasian plate.

Harada et al. (2007a) applied precise meteorological corrections to the data of electro-optical distance measurement using average temperature and humidity observed at both end points of the baseline. By the corrections the variance was reduced by 1/3. Harada et al. (2007b) analyzed GPS and electro-optical distance measurement data obtained by Hot Springs Research Institute. Long-term trends in these data changed in 2000 or 2001. Harada et al. (2008) calculated crustal strains around Kanagawa prefecture based on the method by Sagiya et al. (2000) using the data of GEONET. Compressional strains are detected around Miura Peninsula and Ashigara plain besides remarkable dilatational strains associated with the earthquake swarms in Hakone volcano in 2001 and 2006.

Park et al. (2009) interpreted the Kyushu-Palau Ridge with excess mass buoyancy, which is caused locally by large tectonic stress at the contact zone between the subducted ridge and the base of the overriding plate, using a seismic reflection profile, magnetic anomaly, seafloor topographic features and other geophysical characteristics. Park et al. (2010) found a low seismic velocity zone from a large volume of three-dimensional seismic reflection data along the Nankai accretionary prism. They estimated the size of the low velocity zone and discussed its characteristics.

Shestakov et al. (2010) studied the present tectonics of Northeast Asia using GPS. The obtained results favor the existence of a few separate blocks and a more sophisticated structure of the proposed Amurian microplate in comparison with an indivisible plate approach.

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### 6.1.2 Interseismic Motion

Ozawa et al. (2007) found a slope change of the position time series at GPS sites in Iwate Pacific coastal area, northeast Japan. Based on the position time series, they analyzed the time evolution of a coupling state on the plate boundary between the continental plate and the subducting Pacific plate. Their result indicated a possibility of recovery of slip deficit rate off the coastal area of Iwate, northeast Japan.

They argued that this recovery occurred within a short period of time, if this slip deficit recovery hypothesis is right.

Nishimura et al. (2007) estimated motions of rigid crustal blocks and coupling on their boundary faults in Kanto and Izu regions using GEONET GPS data. They found that the Izu microplate rotated rapidly clockwise at 10 degree/Ma with a rotation pole relative to the central Japan block located just north of its northern boundary.

Jin et al. (2007) applied an inverse method using the spectral decomposition of the Green's function to the estimation of a slip distribution. Numerical simulations along the Philippine Sea plate boundary in southwest Japan suggested maximum back slip rate of about 7 cm/yr, and areas of strong coupling confined between depths of 10 and 30 km.

Tabei et al. (2007) estimated distribution of interseismic plate locking on the Nankai subduction plate boundary by the inversion of three-dimensional crustal velocity data from nationwide continuous GPS array. At the same time, lateral motion of the forearc sliver along the Median Tectonic Line (MTL) and slip deficit on the MTL fault plane were incorporated into the inversion model.

Abidin et al. (2009) used GPS to study the inter-seismic deformation of three active faults in West Java region (i.e. Cimandiri, Lembang and Baribis faults), and the co-seismic and post-seismic deformations related to the May 2006 Yogyakarta and the July 2006 South Java earthquakes. It was found that the area around Cimandiri, Lembang and Baribis fault zones have the horizontal displacements of about 1 to 2 cm/yr or less.

Wallace et al. (2009) proposed a model for the origin of a previously unexplained, active left-lateral shear zone in southern Kyushu revealed by seismicity and GPS. This study highlights the importance of buoyant indentor subduction in the kinematics and evolution of convergent plate boundary zones through a numerical modeling based on the observation.

Aoki and Scholz (2009) modeled the depth variation of interplate locking at Nankai trough from the three-dimensional interseismic velocity field obtained from continuous GPS data. They found that the brittle-plastic transition zone is broad with depths between 20–40 km. This is consistent with numerical simulation of seismic cycles.

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## 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. The most useful data have been provided by the temporally continuous crustal deformation results from GEONET. In addition, SAR data acquired by ALOS/PALSAR provided spatial distribution of crustal deformation. GEONET detected coseismic displacements of approximately 10 earthquakes from 2007 to 2010.

The Noto Hanto earthquake in 2007 (Mw 6.7) occurred in the Sea of Japan coastal area Noto peninsula, central Japan. The GEONET and InSAR analysis detected the crustal deformation associated with the earthquake. Tobita et al. (2007) provided maps of crustal deformation and a fault model of the earthquake. Ozawa et al. (2008a) reported a slip distribution on an earthquake fault using the detected crustal deformation by GEONET and InSAR. The Niigataken Chuetsu-oki earthquake in 2007 with JMA magnitude of 6.8 occurred north off Kashiwazaki, Niigata Prefecture on July 16, 2007. Nishimura et al. (2008b; 2010) constructed fault models of this earthquake using GPS, InSAR, and leveling data. Nishimura et al. (2010) concluded a combination of a large southeast-dipping fault and a small northwest-dipping fault explained the observed deformation. Nishimura et al. (2008a) found not only a large deformation near the source area but also a local uplift in the region of active folding, 15 km east of the earthquake epicenter in SAR interferograms. This uplift suggests the episodic growth of active folds. The Iwate-Miyagi Inland earthquake in 2008 occurred on June 14, 2008 with a moment magnitude of 6.9. GPS, leveling, and In-SAR surveys detected the coseismic deformation from this earthquake. By inverting the coseismic deformation data, Ozawa et al. (2008b) estimated the location of an earthquake fault and slip distribution on the fault.

GSI makes fault models also for major earthquakes outside Japan using remote sensing data. Tobita et al. (2009) generated a fault model of the 2007 southern Sumatra earthquake using PALSAR interferogram and estimated that the length of the seismic gap offshore Padang is about 370 km.

GSI studied the slip-events on the subducting plates in Japan which the existing GPS network is able to detect. Suito (2007) studied detectability of interplate fault slip in the Tokai district by current GEONET, and concluded that detectable minimum size of interplate fault slip in Tokai area is Mw 5.6 in an limited area and around Mw 6.0 or larger in most of the area.

Nishimura (2009) re-examined geodetic data including leveling, tide-gauge, triangulation/trilateration, and repeated EDM data to clarify the crustal deformation of the 1973 Mw=7.8 Nemuro-oki earthquake. The estimated slip distribution suggests a 50 km-long gap in the coseismic slip between the 1973 Nemuro-oki and the 2003 Tokachi-oki earthquakes along the Kuril trench.

Ozawa (2008) applied InSAR using ALOS/PALSAR data to investigate deformation of the 2007 Chuetsu-oki earthquake. Assuming that the fault plane dips to the southeast, a fault-slip distribution was estimated from InSAR and GPS deformations. The largest fault-slip was estimated to the southwestern deeper part of the mainshock hypocenter. In the northern part of the focal region, the fault-slip was dominant at depths of 5–15 km, but it was limited to shallower depths in the southern part of the focal region.

Hao et al. (2009) investigated fault-ruptures of the Wenchuan earthquake from field investigations and InSAR analysis. Fault-slip distribution estimated from InSAR result was consistent with results of field investigations, and their combination suggested that the two coseismic fault zones ruptured with an irregular surface distribution accompanied by crustal deformations.

Aoki et al. (2008) detected co-seismic deformation signals due to the 2007 Chuetsu-oki earthquake with the use of ALOS/PALSAR, and derived a fault source model consisting of multiple segments. Furuya et al. (2010b) studied crustal deformation signals associated with the 2007 Chuetsu-Oki earthquake in Niigata, Japan, using ALOS/PALSAR InSAR data. The observed signals not only revealed the main shock fault source but also illustrated a transient growth of active fold belt more than 20 km away from the epicenter. Furuya et al. (2010a) studied coseismic deformation signals for the 2008 Wenchuan earthquake based on the ALOS/PALSAR data. The obtained signals were consistent with in-situ measurement data, and a fault source model was developed.

Furuya (2008) reviewed satellite remote sensing of earthquakes and volcanic eruptions with particular emphasis on synthetic aperture radar imagery. Takada et al. (2009) presented a detailed image of the ground displacements associated with the 2008 Iwate-Miyagi Nairiku earthquake derived from pixel-offset tracking approach to ALOS/PALSAR data. Besides the fault trace due to the west-dipping fault plane, they detected significant signals that were likely to be an east-dipping fault nearby Kurikoma volcano, where quite a few aftershocks occurred.

Sato et al. (2007) discussed the effect of elastic inhomogeneity on the surface displacements due to subsurface dislocations based on three-dimensional finite element modeling for the northeastern Japan. The discrepancies in the surface displacements between homogeneous and inhomogeneous cases are more than 20 % and can be as large as ~40 %. Sato et al. (2010) estimated the afterslip distribution following the 2003 Tokachi-oki earthquake from GPS and PG (pressure gauge) data by using Green's functions for an inhomogeneous elastic space with subsurface structure for the northeastern Japan.

Obtained distribution of the afterslip is significantly different from that based on the Green's functions for a homogeneous elastic space.

Fukushima et al. (2008) detected coseismic deformation of the 2007 Noto peninsula earthquake and presented a fault model. Hashimoto et al. (2008) studied coseismic deformation of the 2006 Mozambique earthquake using Envisat images and presented a fault model. They also revealed a postseismic deformation along the surface rupture. Hashimoto et al. (2010) revealed coseismic deformation of the 2008 Wenchuan, China, earthquake using ALOS/PALSAR images and presented a fault model.

Reddy et al. (2009) investigated the post-seismic crustal deformation caused by the Sumatra earthquake on December 26, 2004, to understand the rheology of the crust and mantle. Subsequent to this earthquake, the post-seismic deformation in Andaman and Nicobar region was monitored using GPS. The post-seismic transients were obtained and the viscoelastic modeling was carried out. Post-seismic flow at a depth of 55–60 km with low viscosity of the order of $10^{19}$ Pa s can explain observed far field motion.

Fukuda et al. (2008) developed a new time-dependent inversion method for imaging transient fault slips from geodetic data, employing a new filtering technique, a Monte Carlo mixture Kalman filter (MCMKF), and applied it to time-dependent inversion. The results indicated that MCMKF yields better state estimates than the Kalman filter.

A large interplate earthquake (Mw7.7) occurred in the south of Java Island on July 17, 2006, and caused a significant tsunami. Kato et al. (2007) made GPS observations and tsunami heights measurements during the period from July 24 to August 1, 2006. Results of these data suggested that the earthquake might have been a "tsunami earthquake".

Takahashi et al. (2007) compared strain seismograms of the 1978 and 2005 Off-Miyagi earthquakes observed by the same strainmeter at Erimo, northern Japan. High-rate-sampled strain data indicated the 2005 earthquake had less than half the seismic moment of the 1978 event. Takahashi and Kasahara (2007) estimated slip distribution and seismic moment of the 2006 Central Kuril earthquake (M8.0) by remote GPS data. The result implies that there remains a seismic gap between this event and the 1952 great Kamchatka earthquake, large enough for an M>8 earthquake. Vasilenko et al. (2008) estimated fault model for the 2007 Nevelsk earthquake, southeast off Sakhalin Islands, Russia, by INSAR and aftershock distribution data.

Ohta et al. (2008a) determined a coseismic fault model of 2007 Chuetsu-Oki earthquake from the GPS data. They also discussed postseismic GPS time series characteristics. Ohta et al. (2008b) determined a coseismic fault model of 2008 Iwate-Miyagi Nairiku earthquake from a dense GPS network. They found the mainshock occurred on an undefined fault system near an identified active fault. They also detected very large displacement near the epicenter which reaches more than 1.5 m in vertical components.

Hiramatsu et al. (2008) estimated the coseismic vertical crustal movement of the 2007 Noto Hanto earthquake along the northern and western coast of the Noto Peninsula from the distribution of littoral organisms and GPS data, and presented a rectangular fault model with a uniform slip.

Shibata et al. (2010) discussed groundwater level changes in and around Hokkaido due to the Noto

Hanto Earthquake in 2007 (Itaba et al., 2008a), the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes (Itaba et al., 2008b), and the earthquakes at the Dogo Hot Spring, Japan (Itaba et al., 2007).

Kobayashi et al. (2009) studied location and types of surface rupture due to the 2008 Wenchuan earthquake, China, by applying pixel-offset tracking approach to ALOS/PALSAR data. The result was consistent with in-situ measurement data.

Abidin et al. (2009) observed the interseismic deformation in West Java region, and the co-seismic and post-seismic deformation related to the May 2006 Yogyakarta and the July 2006 South Java earthquakes using GPS observation. They found that the horizontal displacements around active faults were about 1 to 2 cm/yr or less and coseismic deformation was less than 10 cm.

Hori (2009) proposed a mechanical model for size dependent recurrence time interval of great interplate earthquakes. Hori et al. (2009) proposed a conceptual model for reproducing recurrence-timing variation related to earthquake size. Hori and Miyazaki (2010) introduced a micro asperity with a smaller nucleation size and developed a numerical model to simulate multiscale earthquake occurrence in the northern Japan trench.

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### 6.2.2 Slow/Silent Deformation

The GEONET detected several transient ground displacements associated with slow slip events and postseismic deformation following large earthquakes. The mechanisms of postseismic deformation were analyzed for several earthquakes using geodetic data.

Slow slip events were found offshore of the Boso peninsula, central Japan, in 1996, 2002, and 2007 (Ozawa et al., 2007). The three events occurred in a similar area offshore of the Boso peninsula with time duration of around ten days. Slip propagation from north to south was illustrated by spatiotemporal analysis. The Boso slow slip event suggests existence of characteristic slow slip events at time intervals of around 6 years.

Suito and Ozawa (2009) reported that the postseismic deformation caused by the 2004 off southeast Kii peninsula earthquake affects the estimation of ongoing slow slip event in the Tokai area. After removing the postseismic effects, they concluded that the Tokai slow slip event ended in summer 2005 with its magnitude reaching 7.2. Suito and Freymueller (2009) reported that postseismic deformation following the 1964 Alaska earthquake continues more than 40 years, and the present day velocities contain a significant component of postseismic deformation of viscoelastic relaxation.

In addition to these events in subduction zones, transient deformation was also observed in inland areas. Nishimura (2010) examined leveling data for about 110 years in Chuetsu region, Niigata Prefecture. They found a local uplift along the anticline axis of active folds with a rate of 2–4 mm/yr started about 40 years ago. The episodic uplift was accelerated by the Niigataken Chuetsu-oki earthquake in 2007.

Kimura et al. (2008) investigated strain changes caused by the short-term slow slip events (SSE) which were observed by the JMA strainmeters. The locations of the slip estimated by the strain changes agree with the source region of the low frequency earthquakes. Yamamoto and Kobayashi (2009) studied the strain excursions at Tsuruga and Imazu stations around 2000 and 2005 which became evident by removing seasonal changes and an exponential trend. These may have been caused by the slow slip events in the Tokai district from 2000 to 2005. Kobayashi (2010) reported a small-scale, long-term slow slip event which occurred in the western Shikoku in 2005. The slip region is adjacent to the region of the long-term slow slip of the Bungo Channel.

Kobayashi and Hashimoto (2007) studied temporal change of strain rate in the Chubu district, central Japan, during the period encompassing the Tokai slow event and pointed out its correlation with seismicity changes in the surrounding region. Hashimoto et al. (2008) revealed a detailed postseismic deformation following the 2007 Noto peninsula earthquake using data from dense observation of GPS and showed the dominance of afterslip over poroelastic rebound. Hashimoto et al. (2009) studied postseismic deformation following the 2004 Sumatra-Andaman earthquake using continuous GPS data in southeast Asia and presented temporal evolution of afterslip on the plate interface along the Sunda trench.

Matsumoto et al. (2007) calculated hypothetical groundwater-level anomalies associated with a hypothetical preslip prior to the anticipated Tokai earthquake and evaluated the detectability using the groundwater observation network of GSJ. Ohtani et al. (2009) calculated hypothetical strain anomalies associated with a hypothetical preslip prior to the anticipated Tonankai-Nankai earthquakes and evaluated the detectability using the strainmeter network of GSJ. Itaba et al. (2010) detected a strain change by slow slip event at Kii Peninsula.

Obara and Sekine (2009) showed the episode of tremor and slow slip that started in the southern Mie area, central Japan and propagated through the Ise Bay area to the Aichi area over 200 km in the strike direction of the subducting Philippine Sea plate in 2006. The observed tilt records can be reproduced well with a sequence of migrating slow slip fault models. This event is the largest and longest-lasting ETS event ever in southwest Japan.

Hirose and Obara (2010) demonstrated slip distributions of seven short-term slow slip events that occurred in the western Shikoku region, southwest Japan from 2002 to 2007 by applying a time-dependent slip inversion method to National Research Institute for Earth Science and Disaster Prevention (NIED) Hi-net tilt deformation records. It was found that the slow slip propagates together with the migration of non-volcanic tremor sources. Moreover, the repeating slip events share almost the same patch-like area on the plate interface.

Sekine et al. (2010) conducted a systematic geodetic inversion of NIED Hi-net tilt records of short-term slow slip events (SSEs), and reported the source parameters of rectangular fault models of 54 SSEs from 2001 to 2008. The along-strike variations in the recurrence intervals, event sizes, and interplate coupling coefficients in the ETS source region are observed.

Applying both stacking and time-series analysis to ERS SAR data archive, Furuya et al. (2007) detected actively deforming signals on the order of 2–3 mm/year in the Needles District, Canyonlands National Park (Utah), USA, with an estimated precision of less than 1 mm/year. Besides a subsiding signal to the SW in the Needles, a localized uplifting signal was found along the Colorado River. Using Envisat InSAR data, Furuya and Satyabala (2008) discovered a long-lasting afterslip signal associated with the earthquake on October 2005 at the Chaman fault, ~900 km long left-lateral strike slip fault from Afghanistan to Pakistan. Despite its moderate main shock magnitude (M5.0), the afterslip signal lasted more than a year. Takada and Furuya (2010) examined the crustal deformation signals from the InSAR data based on JERS1 satellite. It turned out that the 1996 Onikobe earthquake swarm accompanied complex and multiple fault segments that were not only seismic but partially aseismic.

Iinuma et al. (2008) studied the postseismic slip associated with the 2007 Chuetsu-oki Earthquake (M6.8; 16 July, 2007) at the southeastern rim of the Sea of Japan based on GPS observation. It was revealed that the postseismic slip on the faults occurred at a downdip and updip extension of the coseismically slipped portion. Iinuma et al. (2009) detected an aseismic slip event on the intraplate Dedana Fault that was triggered by the Iwate-Miyagi Nairiku earthquake (Mw6.8; 13 Jun, 2008) on a nearby but separate fault using GPS observations. They also suggested that this slip was triggered by the stress change from the mainshock.

Uchida et al. (2009) estimated the spatio-temporal distribution of quasi-static slip on the plate boundary southeast off Hokkaido from detailed analyses of repeating earthquakes and GPS data to reveal that the afterslip is distributed outside the asperity of the 2003 Tokachi-oki earthquake (M8.0), and that the 2004 off-Kushiro (M7.1) earthquake occurred near the edge of the afterslip area.

Matsumura et al. (2008) obtained a detailed distribution of areal dilatation from very dense GPS network data at the Tokai region where a huge earthquake is presumed to occur in the near future. They verified the asperity distribution on the earthquake fault obtained from seismic data by the dilatation distribution obtained.

Mitsui et al. (2009) developed an interplate frictional model consisting of two stages: (1) the estimation of initial condition using a long term data and (2) the successive data assimilation. They applied the model to observed data. Mitsui et al. (2010) developed a quantitative earthquake generation model to assimilate the earthquake generation cycle based on crustal deformation data and other observational data.

Ariyoshi et al. (2009) recognized slow earthquakes with low-frequency which occurred at about 30 km in deep in SW Japan and Cascadian margin. From the characteristics of the events, they formulated a three-dimensional subduction model and succeeded in explaining observed events. Ando et al. (2010) defined and classified deep low-frequency earthquakes, nonvolcanic tremor and regular earthquakes. They showed a physical model to explain these features in a simple framework.

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### 6.2.3 Volcanic Activities

GSI performed control point survey in Io To Island in February 2009 and updated geodetic coordinates of the control points; horizontal coordinates in seven years and heights in 41 years. Hiraoka et al. (2009) revealed that the linear rate of uplift at the two GPS-based Control Stations observed by GPS for the past 12 years was almost the same as the mean rate from the control surveys for an interval of 41 years. They also demonstrated that both GPS campaign measurements and control point surveys showed the heterogeneous geographic pattern of uplift rates over the island and that the uplift has been continuously observed in the entire island from a number of surveys since the early 20 century.

Nishimura and Murakami (2007) re-analyzed leveling data associated with the earthquake swarms in 1930 east off the Izu Peninsula. The observed uplift is explained by a near-vertical tensile fault suggesting dike intrusion east off Ito.

Daita et al. (2009) reported the remarkable changes which was observed by tiltmeters installed in the Hakone caldera during the 2001 intense swarm activity. It is proposed that the crustal deformations were produced by two shallow open cracks and a Mogi-source at a depth of 7 km. Harada et al. (2009a) analyzed GEONET data around Mt. Hakone and Mt. Fuji since the 2001 Hakone swarm activity, and investigated pressure sources that produced crustal strains associated with the swarm activities in 2001, 2006, and 2008. Harada et al. (2009b) investigated influence of the pressure sources that caused crustal strains during the intense swarm activity in 2001 on the occurrence of the supposed disastrous earthquake in western Kanagawa Prefecture based on different models. Iwakuni et al. (2009) analyzed crustal deformations around the Hakone volcano using GPS data of Hot Springs Research Institute and Geographical Survey Institute. Whereas crustal deformations associated with 2001 and 2006 earthquake swarms were detected, crustal deformations associated with other earthquake swarms in the period from 2001 through 2007 were not detected. Harada et al. (2010) investigated temporal changes in dilatational strains and the activity of low-frequency earthquakes around Mt. Fuji and the Hakone volcano. It is pointed out that both cumulative strain and cumulative number of low-frequency earthquakes have been increasing around Mt. Fuji. On the other hand, no clear relationship is seen between the change in the extensional strain and the change in the activity of low-frequency earthquakes around the Hakone volcano.

Yamamoto et al. (2008) carried out observations of magnetism, deformation, gravity, and self-potential in Adatara volcano. An inflation of the crater in Adatara before 2000 and a deflation after 2000 were observed by GPS. A gravity increase was observed in the crater from 2001 to 2005, and the amount of change was larger than expected from the height change. Takagi et al. (2010) conducted relative microgravity surveys at Izu-Oshima Volcano from 2004 to 2009. The gravity changes tend to decrease near the northern margin of the summit caldera, and the rates of negative gravity changes reached as much as 0.015 mgal/year. Assuming the Mogi model, they estimated the pressure increase at a depth of 3.65 km.

Fukushima et al. (2009) gave a quantitative interpretation of ground subsidence associated with the mud eruption in east Java on the basis of interferometry of ALOS/PALSAR images. Fukushima et al. (2010) studied dyke intrusion in Piton de la Fournaise volcano using mainly the results of interferometric analysis of RADARSAR-1 images.

Yoshitake and Nakao (2008) estimated strain of NW-SE tension and NE-SW contraction around Kirishima Volcano, Kyushu, Japan from GEONET coordinates calculated by Bernese GPS Software Ver. 5.0 in the period from April 1997 to November 2006.

Ozawa and Taniguchi (2007) detected crustal deformation using Interferometric SAR (InSAR) to investigate the volcanic activity of Baitoushan Volcano. From Envisat/ASAR pair of 15 Oct. 2004 and 4 Nov. 2005, slant-range shortening was detected in 5 km range from the summit. Inversion analysis using InSAR result suggests the inflation of magma source located to 5km depth just under the summit. Its location corresponds to the area where seismic swarms occurred in this period. Ozawa et al. (2007) detected crustal deformation associated with the huge uplift event which started from mid-2006 in Iwo-jima, using InSAR with ALOS/PALSAR data. In three months from the start of the event, a slant-range change suggesting that the whole island had uplifted was detected. After that, uplift accelerated, and uplift exceeding 40 cm in three months was detected. Especially, it seems that crustal deformation concentrates in fault zones surrounding north district of island.

Using a time-series analysis technique for SAR data, Furuya (2007) detected subsiding signals at the caldera floor in the Izu-Oshima volcano, Japan.

Takahashi (2008) proposed a strategy for volcano early warning using relative far-field geodetic data. Eruption magnitude of foreseen eruption is most important information for disaster mitigation. The author proposed a rapid and robust method to estimate predictive eruption magnitude by geodetic data and its application for disaster mitigation operations.

Murase et al. (2007) developed a time-dependent model for volume changes in pressure sources at Asama volcano from precise leveling data collected since 1902. The temporal change in the pressure source beneath Kurofu volcano exhibits a strong positive correlation with the eruption frequency. Savage et al. (2010) found the rotation of the fast axis of seismic velocity during the 2004 unrest of Mt. Asama. Combined with continuous GPS observations, they suggested that the rotation is due to the stress change caused by the dike intrusion during the unrest. Murase et al. (2010) developed a time-dependent model for magma intrusion associated with repeated earthquake swarm activities off the east coast of the Izu peninsula. This model is based on precise levelling, electronic distance measurements and GPS, and sea level observation data for the period 1973–1998.

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### 6.3 Periodic Movements

Munekane (2007) estimated the periodic geocenter motions by the degree-1 loading method using mass-loading deformations measured by GPS and using gravity variations measured by GRACE. He demonstrated that the inclusion of GRACE-derived gravity variations into the degree-1 loading method significantly mitigated the aliasing effect of the unmodeled higher-degree terms of loading deformations, and successfully recovered the periodic geocenter motions that are consistent with those given by the loading models.

Munekane et al. (2009) examined the quality of a newly deployed continuous GPS station, 06S061, in Tsukuba, Japan. The station is directly anchored to the soil at a depth of 190 m so that it is less affected by seasonal poroelastic deformations of aquifers induced by groundwater extraction for irrigation. They found that the poroelastic deformations of aquifers below 190 m, which are to be recorded at 06S061, have peak-to-peak values of about 1 cm, which is half of the total poroelastic deformations of aquifers observed at surrounding GPS stations.

Asai et al. (2009) analyzed the strain data from four observation sites in the Tono area, central Japan, using the tidal analysis program BAYTAP-G and compared the tidal amplitudes of strain with in situ rock properties. The following results were obtained: there is an obvious difference in amplitude and phase of the $M_2$ and $O_1$ tidal strains from four observation sites that are located in the same Toki granite bedrock within a distance of 10 km: there are strong negative correlations between the semi-diurnal E–W, areal tidal strain and in situ rock hardness (shear modulus and Young's modulus), while N–S tidal strain is unrelated. In contrast, strain-steps associated with large earthquakes increase with hardness, as observed at two sites. Asai et al. (2009) consider that the inconsistency of the behavior of the tidal amplitudes and strain-steps may be caused by the heterogeneity of rocks near the borehole strainmeters.

Heki and Kataoka (2008) studied sizes, occurrence times, slip directions, etc. of slow slip events that occur beneath the Iriomote Island approximately every six months, and found significant correlation between event sizes and recurrence intervals.

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## 6.4 In-situ Deformation Observations

Hashimoto (2007) discussed several problems that the continuous crustal deformation study using vaults is now confronting with and proposed a shift to continuous observations in bore-hole.

Ogasawara et al. (2009a) introduced a 5-year project of in-situ monitoring at the closest proximity of hypocenters in South African gold mines, which Japan Science and Technology Agency and Japan International Cooperation Agency fund and South African government endorses. The project includes strain, tilt, stope-closure monitoring, which are going to be compared with acoustic emission, temporal change in ultrasonic wave transmitting through fault. The data are going to be compared with the daily rating of seismic activity, a routine assessment of seismic activity based upon mine's seismic monitoring as well as stress modeling.

Ogasawara et al. (2009b) reviewed the activity over a decade of the Research Group for the Semi-controlled Earthquake-generation Experiments at deep Gold Mines, South Africa (SeeSA). That includes in-situ strain monitoring at the closest proximity of potential hypocenters of mining-induced earthquake. Noted are the multiple examples of slow strain events, some of which are preceded by clear forerunners.

Mukai and Fujimori (2007) estimated the hydraulic properties of fracture zone nearby the Nojima fault by using the observed strain changes due to the water injection experiments, which were performed at the 1800m-deep borehole installed in Awaji Island, Japan. Mukai (2008) investigated environmental noises on the observations of gravity and crustal movements. As one of such environmental noises, amplitudes of the tidal strain in Awaji Island, Japan, were decreased gradually by the hardening of the fracture zone nearby the Nojima fault.

Kobayashi (2010) identified the cause of characteristic volumetric strain and water level changes at Mikkabi as artificial pumping in the well close to the observation point. A model was proposed on the relation between strain and water level changes by pumping.

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## 6.5 Sea-level Change and Glacial Isostatic Adjustment

Kobayashi (2008) examined the sea area divisions defined by Tsumura (1963) to deduce vertical crustal movement using monthly sea level data for the period from 1961 to 2000. The divisions defined by Tsumura were confirmed to be appropriate at most of the stations.

Tanaka et al. (2009) developed a theoretical computation method for postglacial rebounds to include the effects of compressibility in a spherically symmetric earth model. Effects of compressibility on the load Love number are investigated. Tanaka et al. (2011) included the effects of compressibility in a self-gravitating spherical earth model with 3-D viscosity structure. Effects of compressibility on the present-day velocity field due to postglacial rebounds exceed 1 mm/yr in a global scale, which are detectable by GPS.

Tohoku University received funding from Japanese government to work with University of Alaska, Fairbanks on a collaborative project named ISEA (International geodetic measurements in SouthEast Alaska (SE-AK)). The group established 6 new continuous GPS (CGPS) sites across the area during 2006-2007, and to carry out three absolute gravity campaigns at 6 measurement sites. The resulting rheological structure model beneath the study area based on the updated GPS uplifting rates reproduces the gravity change surprisingly very well. CGPS observations at sites in the area show that uplift does not occur at a constant, steady rate. Instead, the ground subsides slightly throughout the winter before uplifting very rapidly from the onset of the spring melt until subsidence begins again the next winter. The amplitude of the seasonal deformation signal that is superimposed on the uplift trend reaches at much as 20–25 mm, corresponding to 40–50 mm peak-to-peak variations in height. Data from the GRACE mission reveal corresponding seasonal variations in the geoid – outside of the equatorial rain forest basins, nowhere on the planet features such extreme changes in hydrological loading. They also developed an improved ocean tidal model for the region, and deployed ocean bottom pressure sensors to collect data that will improve the tidal model further.

Based on GPS data sets obtained at 91 sites in SE-AK, Sato et al. (2010) revaluated the rheological structure beneath SE-AK, and confirmed the existence of the very thin lithosphere (50–60 km in thickness) and the very low asthenospheric viscosity that is equal to or smaller than $10^{19}$ Pa s.

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## 7. Marine Geodesy

The GPS/Acoustic seafloor geodetic observation technique has made a notable progress recently. Positional precision better than several centimeters has been attained through efforts to improve the accuracy in both software and hardware. Fujita (2007) describes the outline of the observation and major results.

Japan Coast Guard, The University of Tokyo, Tohoku University and Nagoya University have been developing a precise seafloor positioning system using a GPS/Acoustic combined technique. Sato et al. (2008) reported the major results of the observation and discussed further efforts for more precise and stable results.

JHOD has been using Interferometric Translocation (IT) method composed by Colombo (1998) for KGPS analysis of seafloor geodetic observation. Kawai et al. (2007) reported current status and foresight about KGPS analysis using the IT method.

Ishikawa and Matsumoto (2007) summarized data processing of XBT, XCTD and CTD measurements for calculating underwater sound speed for seafloor geodesy. Matsumoto et al. (2007) proposed a new method of simultaneously estimating the bias of acoustic transducer installation and positions of the seafloor reference points. Significant biases depending on the devices used were detected. The proposed method improved the accuracy of position estimation of seafloor reference points.

Matsumoto et al. (2008a) proposed a new method for determining seafloor station position. This method simultaneously estimates the position of a seafloor reference point for each epoch using multi-epoch observation data. It is expected that this method provides more precise and stable results than the ordinary single-epoch method.

Matsumoto et al. (2008b) reported the result of seafloor geodetic observation off Fukushima. The result shows an intraplate crustal movement velocity of 3.1 cm/year toward west, implying weak interplate coupling in this region. Matsumoto et al. (2008c) reported the result of seafloor geodetic observation off Tokai District. The result shows an intraplate crustal movement velocity of 2.9 cm/year toward NW. This result is in a realistic range and implies strong interplate coupling around this region.

Mochizuki et al. (2007) reported the result of tank tests which were conducted to evaluate the ranging characteristic curves of the acoustic transducers. Obtained curves were used to deduce the acoustic phase centers of the transducers. A next-generation seafloor geodetic observation system has been developed. The main idea of the system is to utilize the technique of underwater robotics in place of a research vessel. Mochizuki et al. (2008) reported the trials with the prototype of the system.

Kawai et al. (2009) reported installation of an acoustic transducer under the hull of a survey vessel. Sato et al. (2009) evaluated the results of seafloor geodetic observation using a hull-mounted acoustic transducer. The results show that the observation efficiency and spatial distribution of data were greatly improved because the hull-mounted system enables us to conduct acoustic ranging observation while sailing. It is expected that more stable results are obtained with a shorter duration of observation.

Saito and Sato (2009) evaluated the effect of reducing the frequency of undersea sound velocity measurements on the accuracy of positioning a seafloor reference point. It was suggested that well-balanced distribution of acoustic measurement points would allow us to reduce the frequency of undersea sound velocity measurements from hourly to every four hours, without degrading the accuracy of seafloor positioning.

Saito et al. (2010) evaluated the effectiveness of using the rapid orbit in KGPS analysis in seafloor geodetic observation by comparing the positions of the seafloor reference points from the rapid orbit with those from the final orbit. The results showed that the root-mean-square of the horizontal distances between the two positions was 3 mm, which was within the precision of seafloor positioning using the final orbit.

A seafloor reference point consists of three or four acoustic mirror-type transponders installed on the seafloor. Each transponder has an acoustic signal pattern for identifying itself. Sato (2010) reported the background and technical overview of the extension of acoustic signal patterns for identifying the transponder.

Sato et al. (2011) has detected seafloor movements associated with, and subsequent to, the 2005 Off-Miyagi Pref. earthquake. The time series after the end of 2006 shows a west-northwestward linear trend equivalent to the velocity of 5.7 cm/year relative to the Eurasian plate. This result implies that the interplate locking was restored in the rupture area of the event around 2007.

Japan Coast Guard (2009a) showed the latest result of seafloor geodetic observation in Sagami-Bay, off Miyagi and Fukushima and along Nankai Trough as of July, 2008, and introduced the observation system using a hull-mounted acoustic transducer. The result shows the crustal movement velocity in Sagami Bay was 4.1 cm/year toward NW. Japan Coast Guard (2009b) showed the latest result of seafloor geodetic observation off Miyagi as of March, 2009, and compared the result with the crustal velocity vectors calculated from the back-slip distribution and cumulative slip distributions after the 2005 off-Miyagi Prefecture earthquake.

Japan Coast Guard (2010a) showed the latest result of seafloor geodetic observation at six stations along the Nankai Trough as of March, 2009. Interplate crustal movement velocities of about 2–5 cm/year toward NW-W are detected at each station. Japan Coast Guard (2010b) reported the results of seafloor geodetic observation off Miyagi and Fukushima as of March, 2009. The results off Miyagi indicate that the strain released by the 2005 earthquake restarted to accumulate after 1–2 years of the post-seismic period. It is the first successful detection of a series of co- and post-seismic processes before the period of the restored constant strain accumulation in the sea area. Japan Coast Guard (2010c) showed the latest results of seafloor geodetic observation off Miyagi and Fukushima as of March, 2010. The results show that interplate crustal movement velocities off Miyagi are about 5–6 cm/year toward NW, while those off Fukushima are 2.2 cm/year toward west.

Ikuta et al. (2008) developed a new geodetic system for monitoring crustal deformation on the ocean floor. They repetitively measured the location of ocean floor benchmarks using the GPS/Acoustic measurement system. They achieved positioning accuracy of 5 cm in horizontal and 10 cm in vertical beneath the 2000 m deep ocean. Fujimoto et al. (2008) reported development of GPS/A positioning system for seafloor crustal movements. Osada et al. (2008) developed a seafloor acoustic ranging system for geodetic monitoring of an active fault on the seafloor, and carried out a trial experiment.

Kido (2007) proposed a new layout of GPS/Acoustic survey with 5 seafloor transponders, which can resolve lateral gradient of sound speed structure in ocean through an inversion analysis. Kido et al. (2008a) developed a new algorithm to estimate uncertain equipped position of a motion sensor in GPS/Acoustic measurement, the data of which were utilized in the analysis and contributed to improve the buoy attitude monitoring. Kido et al. (2008b) showed that GPS/Acoustic seafloor positioning with 3-4 seafloor acoustic transponders can well monitor temporal variation of sound speed in ocean in comparison with repeated XBT measurements.

Hino et al. (2009) described continuous long-term seafloor pressure observation which was started for detecting slow-slip events in Miyagi-oki on the landward Japan trench slope, and simulated variation of the detectability with distribution of the pressure sensors.

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## 8. Earth Tides and Ocean Tidal Loading

In recognition of growing importance of the tidal system consistency among different height determinations by spirit leveling and space geodesy techniques, Kuroishi (2010a; 2010b) has quantitatively evaluated the effects of astronomic tides and ocean tidal loading on precise leveling over long distances along some typical routes of first-order leveling survey in Japan. The results show that temporally changing parts of the cumulative effects of astronomical tides along the routes are comparable to or even larger than, but not linearly related to, their permanent parts, that those total cumulative effects possibly enlarge closure errors in leveling loops, and that the cumulative effects of ocean tidal loading are generally minor but may become significant towards the ocean in high tide areas.

Ito et al. (2009) figured out a high resolution mapping of the Earth tide response base on a GPS array in Japan. The spatial distribution of the observed Earth tide response reflects subsurface structure. The result suggests that it is possible to place constraints on the subsurface structure using GPS-derived tidal information.

Ohta et al. (2008) investigated a tsunami loading effect deduced from kinematic GPS and a broadband seismometer for the 2004 Sumatra-Andaman earthquake. Whereas it was difficult to detect the displacement by kinematic GPS data, a broadband seismometer succeeded in detecting tilting caused by tsunami loading effect.

Ocean tide models in Southeast Alaska used to be poorly determined. Inazu et al. (2009) and Sato et al. (2008; 2009) succeeded in developing accurate regional models. Correcting ocean tidal loading effects by using the new models remarkably improves the standard deviation of the residuals in the absolute gravity and GPS observations. It also contributes to improving the accuracy of the discussion of glacial isostatic adjustment.

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## 9. Application to Atmospheric, Ionospheric and Hydrological Researches

GSI has been investigating the application of numerical weather prediction (NWP) models to evaluation of positioning errors due to modeling errors for tropospheric delay in GPS analysis. Using a high-resolution NWP model at a spatial resolution of 2 by 2 km horizontally and at temporal intervals of one hour, Ishimoto and Munekane (2009) showed that positioning errors estimated from the model were consistent with anomalous temporal position changes in GPS solutions observed locally at some GEONET stations, suggesting the potential of high-resolution NWP models for application to evaluation of positioning errors due to modeling errors for tropospheric delay in GPS analysis.

Satomura et al. (2010) obtained precipitable water vapor (PWV) changes from GPS data at Bangkok, Chiang Mai, Khon Kaen, KogMa and Phuket between 2001 and 2006. They compared the obtained PWV with air pressure and temperature data, and also estimated onset and offset times of the monsoon from the PWV data.

Imamura et al. (2008a; 2008b; 2009; 2010) conducted radio occultation observations of the electron density near the lunar surface during the SELENE (Kaguya) mission using the Vstar and Rstar sub-satellites, and establishment of the morphology of the lunar ionosphere and interpretation of its relationship with various conditions are on the way.

Water vapor molecules included in the exhaust gas of ascending rockets and missiles make localized depletion of electrons in thermosphere or ionosphere. Furuya and Heki (2008) detected this phenomenon for the first time using a dense GPS array in Japan after the launch of the eighth H-IIA rocket in 2006. Ozeki and Heki (2010) found ionospheric “holes” along the tracks of two North Korean missiles using data from the GEONET GPS stations.

Using the GEONET GPS array, Astafyeva and Heki (2009) studied coseismic ionospheric disturbances associated with three earthquakes in the Kuril Islands of different focal mechanisms, and found that positive initial change in electron density as in thrust earthquakes reverses in normal fault earthquakes. Astafyeva et al. (2009) found two distinct components of coseismic ionospheric disturbances with different propagation velocities. They suggest that the slower component is caused by direct acoustic waves from focal regions, and the faster component is excited by the Rayleigh surface waves.

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## 10. Planetary Geodesy

By comparing J3 components in time-variable gravity and terrain height by Mars Global Surveyor, Matsuo and Heki (2009) recovered the seasonal variation (i.e. densification due to compaction) of the carbon dioxide snow in the Martian polar caps.

Araki et al. (2008; 2009a; 2009b; 2009c), Ishihara et al. (2008), and Tazawa et al. (2009) derived a global lunar topographic map with a spatial resolution finer than 0.5 degree using data from the laser altimeter (LALT) on board the Japanese lunar explorer SELENE (Kaguya), and revealed unbiased lunar topography for scales finer than a few hundred kilometers.

RISE Project of National Astronomical Observatory of Japan cooperated with JAXA and universities proposes instruments measuring lunar rotation: Inverse VLBI, and LLR (Lunar Laser Ranging) and ILOM (In-situ Lunar Orientation Measurement), on board SELENE-2 and successors, which will be launched as a Japanese lunar landing mission following the successful SELENE (Kaguya), in order to investigate the lunar mantle and the core. (Noda et al., 2008a; Noda et al., 2008b; Hanada et al., 2009; Petrova et al., 2008; 2009a; 2009b). They also propose observation of Mars' rotation as a part of future Japanese Mars mission by extending the experiences accumulated in the lunar missions (Harada et al., 2010).

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## 11. Regional Geodetic Activities

Kato et al. (2008) reviewed an international scientific program called “Restoration program from giant earthquakes and tsunamis” which established a researchers’ network of the 2004 Sumatra-Andaman earthquake that devastated the countries around the Indian Ocean.

GSI has been participating in the Permanent Committee on GIS Infrastructure for Asia and the Pacific (PCGIAP) to assist its regional geodesy programs toward creation of a geodetic reference frame and prevention/mitigation of damages due to natural disasters as large earthquakes (Matsuzaka et al., 2008; 2009; 2010). Continuous GPS observations on the Pacific region have been conducted by GSI at three monitoring sites: Tarawa, Kiritimati in Republic of Kiribati and Rarotonga in Cook Islands. Observation in Mangareva in French Polynesia was temporarily stopped in September 2010. Crustal deformations monitoring center (CDMC), originally a data center of GSI, has archived raw data of continuous GPS observations from these stations and supported providing raw data to Asia-Pacific Regional Geodesy Project (APRGP) and Asia Pacific Reference Frame (APREF). Asia Pacific Reference Frame (APREF) is a newly launched project of PCGIAP, aiming to support many geospatial applications with accurate geodetic frame. GSI participated in APREF as one of the collaborators in network station division of PCGIAP. Data provision of CDMC is available for the participating members in PCGIAP as well as scientific research communities via the web at the URL http://pasia.gsi.go.jp/RINEX_Download/top.HTML. Data from Rarotonga has been transferred to CDMC through a commercial network since April 2010. Furthermore, GSI has newly deployed seven continuous GPS observation sites, namely five sites in Indonesia and two sites in Philippines, based on cooperation with local organizations of those countries. Those seven sites are operational for monitoring, mainly to detect crustal deformations around active faults. The data obtained at those sites are also archived in CDMC.

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