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THE GEODETIC SOCIETY OF JAPAN

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The electronic file of this report will be available online.

Contents

1. Introduction

This report summarizes the geodetic activities in Japan for the period from January 2011 to December 2014. 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 2015 to be held in Prague, Czech Republic, June–July 2015.

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. T. Hobiger, Y. Tanaka, T. Ito and M. Sato were the winners of the Tsuboi Prize, and The Group for development of Experimental Geodetic Satellite (EGS) represented by H. Hashimoto, and The seafloor and terrestrial geodetic observation Group represented by H. Fujimoto, respectively, were the awardees for the Group Tsuboi Prize.

The 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0) occurred on March 11. Geodetic techniques achieved overwhelming success in understanding the whole picture of this earthquake. Large-scale crustal deformation over a wide area of the eastern Japan was detected by GEONET, Japan's dense Global Navigation Satellite System (GNSS) network. The new Survey Results of GEONET stations were published on May 31, 2011 and those of triangulation stations and leveling bench marks on October 31, 2011 respectively. The seafloor geodesy such as ocean bottom pressure gauge and GPS/acoustic brought direct evidence of the large fault slip, which caused devastating tsunami, and renewed our knowledge of megathrust earthquakes. The L-band SAR (Synthetic Aperture Radar) carried by ALOS (Advanced Land Observing Satellite) succeeded in acquiring detailed images of the triggered events before the termination of its operation on May 12, 2011. The next L-band SAR satellite ALOS-2 was successfully launched on 24 May, 2014.

In March 2014, The Geospatial Information Authority of Japan (GSI) completed constructing a new VLBI antenna at Ishioka, which is fully compliant with VGOS (VLBI Global Observing System) promoted by the International VLBI Service for Geodesy and Astrometry (IVS). In October 2014, GSI hosted the 32nd IVS Directing Board meeting and an inauguration ceremony of the new VLBI antenna. The antenna will take over the role of Tsukuba 32-m to maintain the Global Geodetic Reference Frame. GSI also contributed to the establishment of the Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) to foster the collaboration in the aspects of VLBI in the region.

The International Workshop on Laser Ranging has been held almost every two years all over the world, and the 18th workshop came to Japan from 11 to 15 November, 2013. 150 participants from 26 countries gathered in Fujiyoshida city, at the foot of Mt Fuji. The workshop subtitle is set to “Pursuing Ultimate Accuracy & Creating New Synergies” where the participants actively discussed how to meet the 1-mm and 0.1-mm/year goal of Global Geodetic Observing System and saw a very wide variety of what laser ranging technology can do.

The GENAH2014 international symposium, sponsored by the IAG Commission 3, was held 22 - 26

July 2014 in Matsushima, Japan. 130 geodesists from 16 countries gathered, to discuss the role of geodesy in earthquake and volcanic studies, natural hazard assessment, and disaster mitigation. In total, 83 oral and 50 poster presentations were made in 7 sessions: Subduction Zone Earthquakes, Earthquake Deformation Cycle, Near Real-Time Warning, Interaction between Earthquakes and Volcanoes, Impact of Great Earthquakes on Reference Frame, Geodetic Techniques in Volcanological Research, and Natural Hazards. Participants also visited damaged area in Ishinomaki city and Onagawa town, where a very high tsunami attacked on March 11 2011 and recovery works are still going on. They stopped at a couple of memorial places, heard related stories and fully realized the impact of this disaster. Participants provided a complete description of the state of the art geodesy applied to natural hazards, and found many take-home questions concerning scientific, technical and social issues through the five-day long discussion.

2. Positioning

GSI has been participating in the IVS as Network Stations, a Correlator, and an Analysis Center. GSI has maintained four VLBI antennas in Japan, i.e., Tsukuba 32-m antenna in Ibaraki, Aira 10-m antenna in Kagoshima, Chichijima 10-m antenna in Ogasawara, and Shintotsukawa 3.8-m antenna in Hokkaido. Tsukuba 32-m antenna, as a main Network Station for GSI, observed 743 IVS sessions in total in 2011-2014. For other regional stations, Aira, Chichijima, and Shintotsukawa antenna also observed 76, 60, and 27 sessions respectively in 2011-2014 (Kawabata et al., 2012; Kawabata et al., 2013; Wakasugi et al., 2014). The Tsukuba VLBI correlator and the Analysis Center processed VLBI data for 430 one-hour Intensive sessions for UT1 determination and 33 Japanese domestic sessions (JADE and JAXA sessions) in total in 2011-2014 (Kokado et al., 2012a; Kokado et al., 2012b; Kurihara and Nozawa, 2013a; Kurihara and Nozawa, 2013b; Kurihara and Hara, 2014a; Kurihara and Hara, 2014b). GSI has revealed drastic change of the position of the Tsukuba 32-m antenna as the co-seismic displacement at the 2011 off the Pacific coast of Tohoku Earthquake (Kurihara et al., 2012). The VLBI result was used for the revision of the survey results of control points in Japan (Hiyama et al., 2011).

Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, operates four VLBI stations named VERA. It is dedicated to geodesy and astrometry. Mizusawa and Ishigakijima stations of the VERA join IVS-T2 international VLBI network. Those two stations also join domestic network JADE which is coodinated by the Geospatial Information Authority of Japan (GSI). Within the VERA network, they carried out geodetic experiments in K band to get the most accurate results. In total, they had about 30 experiments per year. Jike et al. (2012a; 2012b; 2013; 2014) 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, at the marine geodetic control point, and in Izu Shoto area. The observation results in 2011, 2012, 2013, and 2014 are reported in Hydrographic and Oceanographic Department (2011; 2012; 2013;2014).

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3. Development in Technology

3.1 VLBI

Automated VLBI data analysis for rapid UT1 measurement (Hobiger et al., 2011) and observational level combination analysis of multi space techniques were developed based on Space Geodesy Software Package C5++ maintained by a collaboration group of National Institute of Information and Communications Technology (NICT), Hitotsubashi Univ, and Institute of Space and Astronautical Sciences (Hobiger et al., 2014; Hobiger and Otsubo, 2014). A new VLBI data acquisition technique for broadband observation was developed (Takefuji et al., 2012).

GSI has been actively involved in the ultra-rapid UT1 experiments to measure Earth orientation parameters (EOP) in near real-time by using high speed network and well-designed software, e.g., C5++ developed by NICT (Kokado et al., 2012; Kurihara et al. 2013).

In March 2014, GSI completed construction of a new VLBI antenna at Ishioka that is fully compliant with VGOS, which is a new VLBI observing system to be a VLBI component of the Global Geodetic Observing System (GGOS). The Ishioka 13-m antenna has advanced performance as a VGOS station with very high slew speed rate of 12 degrees per second in azimuth direction and broad-band receiving capability ranging from 2 to 14 GHz in radio frequency (Fukuzaki et al., 2012; Fukuzaki et al., 2014). The antenna will be in operation in 2015 and fully involved in the VGOS observation in 2017.

National Institute of Polar Research (NIPR) maintains 11m VLBI antenna at Syowa Station, Antarctica. The antenna has been participating in more than 120 international VLBI sessions since 1998 in the framework of International VLBI Service. It contributes to maintain international terrestrial reference frame and measure plate motions (Doi et al., 2011; Aoyama et al., 2012;2013;2014).

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3.2 SLR

The Shimosato Hydrographic Observatory has been carrying out satellite laser ranging observation since 1982. 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 (2011; 2012; 2013; 2014).

National Institute of Information and Communications Technology (NICT) has made design and development of SLR sub-system such as optical transmit/receive system, range gate generator instruments as well as space segment of retro-reflector array for Japanese missions (Hashimoto et al., 2012; Kunimori et al., 2011;2012).

Otsubo et al. (2011) investigated the optical responses of hollow-type retroreflectors, especially focusing on large-size, single-reflector targets for future lunar laser ranging. An asymmetric dihedral angle offset, 0.65-0.8 arcseconds for one angle, and zeroes for the other two angles, was found effective for retroreflectors larger than 100 mm in diameter. Otsubo et al. (2014) derived new values for the so-called center-of-mass corrections for three geodetic satellites, Starlette and Stella, LARES. The longtime standard center-of-mass correction 75 mm of Starlette and Stella was revealed to be too small for the current laser-ranging stations on average.

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3.3 GPS

3.3.1 GEONET

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

Kimura and Miyahara (2013) made the index of crustal deformations derived from earthquakes occurring between 1996 and 2012 using GEONET data reanalyzed by the latest routine analysis system. They listed 70 earthquakes whose stations observed crustal deformations.

GEONET successfully recorded the displacements by the 2011 off the Pacific coast of Tohoku Earthquake (the 2011 Tohoku-Oki Earthquake hereafter) partly thanks to the extensive management of damaged stations as reported by Oshima et al. (2011). Suito et al. (2011a) found 540 cm southwest movement at the M-Oshika station in Miyagi prefecture by the 2011 Tohoku-Oki Earthquake. They found that the stations located between Hokkaido and northern Kyushu region observed crustal deformation caused by the earthquake.

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. The 2011 Tohoku-Oki Earthquake promote the plan. Since May 10, 2013, almost all GEONET observation stations have proposed GLONASS and QZSS observation data in addition to GPS (Tsuji et al. 2013). They renamed GEONET to "GNSS Earth Observation NETwork system".

GSI and Tohoku University jointly developed real-time fault modeling routines in the real-time analysis system on GEONET: REGARD, and showed that reliable estimation of the coseismic fault model and/or slip distribution on the subducting plate interface will be possible in Japan based on the real-time GNSS data with acceptable latency (Kawamoto et al., 2013; Kawamoto et al., 2014; Yahagi et al., 2014).

Munekane (2013) evaluated tilt-induced monument displacements of GEONET stations, using kinematic GPS time series and found that these displacements show characteristics that are typical of those caused by thermal tilts of the monuments.

Shimada (2012) compares coordinates solutions between the absolute and the relative phase center variation (PCV) models using the GPS Earth Observation Network (GEONET) data in Japan before 1400 GPS week. In the result for the regional network sites and the western Pacific International GNSS Service (IGS) fiducial network sites during 2005 and 2006 the coordinates repeatabilities applying the absolute PCV models are better than those adopting the relative PCVs, although the advantages are not significant for the period between 1996 and 1999. Shimada (2013) evaluates the International GNSS Service (IGS) reprocessed GPS precise ephemeris (repro1) is evaluated applying the Japanese dense GPS network data for the period from September 1996 to December 1999 (173 weeks). Shimada (2013) compares the weekly repeatability of the site coordinates of the Japanese network sites applying the reprocessed orbit with that applying the original IGS final orbit. The repeatability with the reprocessed orbit is better than that with the original orbit in the E-W and U-D components, although not significant compared with the standard error. Shimada (2013) also examined the systematic discontinuity of the station coordinates between the periods of the different reference frames applied in the IGS final orbit, and find that the jump between ITRF94 and ITRF97 is far larger than that between ITRF96 and ITRF97.

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3.3.2 GNSS Data Processing

Hatanaka (2011a) developed a method to derive regional ionosphere delay correction model for Japan from GEONET data. The baseline time-series obtained by applying the model to single frequency GPS data show higher root mean square deviation by 20-30% than the results obtained by analyzing ionosphere-free linear combination. Hatanaka (2012) tuned the ionosphere correction model and showed that better repeatability of height component than dual frequency analysis is achievable by using finer spatial grid of up to 0.2 degrees. Hatanaka (2011b) developed a technique to analyze GPS data of any GPS observation site by forming baseline with a GEONET station as a reference site. By applying routine solutions of GEONET for the site coordinates and troposphere parameters of the reference site, the obtained solutions become compatible with routine solutions of GEONET.

GSI is developing and standardizing new precise positioning techniques which deal with multiple GNSS constellations in order to mainly encourage effective surveys at places where are currently difficult to carry out them using only GPS satellites. To achieve this goal, GSI developed new analysis software named GSILIB (GNSS Surveying Implementation Library) based on RTKLIB (available at http://www.rtklib.com). GSILIB supports to correct several biases occurred in GNSS receivers: L2C quarter-cycle bias, Inter Frequency Bias, Inter System Bias for using single/double differences between GPS and other GNSS (Furuya et al., 2014).

Software based GPS receiver for time transfer application (Gotoh et al., 2014) and real-time GNSS observation by using graphics processing unit (Hobiger et al., 2012) were developed by National Institute of Information and Communications Technology (NICT). In addition, the performance of ray-traced atmospheric delay correction for GNSS PPP processing has been assessed (Ichikawa et al., 2012). Doke et al. (2013) constructed analysis system for the GEONET and their own sites, using Bernese Software, to monitor the crustal deformation in and around Kanagawa Prefecture, Japan. This system automatically outputs daily coordinates, baseline lengths, vectors and strains.

The First Quasi-Zenith Satellite “MICHIBIKI” was successfully launched on September 11, 2010. After the initial functional verification, Wakabayashi et al. (2012) have started the domestic experiments to evaluate performance of the Quasi-Zenith Satellite System (QZSS), especially the effect of QZSS on the improvement of availability for GNSS Positioning, Navigation and Timing (PNT) service.

Ebinuma and Kato (2012) used high rate GPS observations and investigated its characteristic nature in the case that the very high rate up to 50Hz is used for GPS seismometer. They suggested that there could be amplitude and phase shift in the obtained position variations if the data rate is higher than 5Hz and warned that such shifts should be taken into account if the high-rate observation is applied to seismological investigations.

Wang et al. (2013) used a moving rate of variation filter to extract short-term signals from GPS time series in New Zealand, California, and Japan. The precursory information of these signals for large earthquakes is evaluated using Molchan’s error diagram. The results suggest that the GPS signals provide a probability gain of 2–4 for forecasting large earthquakes against a Poisson model. Further tests show that the GPS signals are not triggered by large earthquakes, and that the probability gain is not derived from forecasting aftershocks. This demonstrates that noncatalog information, such as GPS data, can be used to augment probabilistic models based on seismic catalog data to improve forecasting of large earthquakes.

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3.3.3 REGMOS

REGMOS is an abbreviation of Remote GNSS Monitoring System for volcanoes. Since 1997, GSI has developed REGMOS which is a system for observation and monitoring of the three-dimensional crustal deformation around volcanic regions with high accuracy by using positioning signals from GNSS satellites. It can conduct the observation in the area where there is neither ordinary electricity nor telephone service. Until 2010, GSI had improved its communication system, adopted the synthesized control unit in it, and remodeled its cabinet for observation in frigid conditions. 11 REGMOSs are operating at 9 volcanoes as of February, 2015.

REGMOS was developed in 2011 – 2012 for multi-channel monitoring volcanoes such as total magnetic force and tilt. An overhauser magnetometer (OVH-216) was installed in REGMOS at Mt. Fuji. Improving heat insulation of the preamplifier and the way of sensor setting made it possible to acquire stable geomagnetic data. The REGMOS's cabinet that they can take to pieces was developed for the purpose of the immediate and mobile observation.

The other improvements of REGMOS were carried out in 2013 – 2014. First, on-board GNSS receiver in the synthesized control unit was upgraded to the one for multi-GNSS observation. After that, REGMOS became capable of receiving data from Quasi-Zenith Satellites System (QZSS), GLONASS, and other satellites, and then GNSS observation became more stable. Second, the communication system was remodeled, and it became possible to select the best communication system according to the installation location. In areas where terrestrial mobile communication system is available, it became able to send large-capacity data including images taken with REGMOS's network camera at a low cost.

3.3.4 Tsunami Monitoring System

Ohta et al. (2012a) developed an algorithm (RAPiD) to estimate the coseismic fault model for the large earthquake from real-time GNSS data, and applied the algorithm to the 2011 Tohoku-Oki earthquake (Mw 9.0). The estimated fault model with Mw8.7 was obtained within five minutes from the origin time, and close to the actual one. Tsushima and Ohta (2014) reviewed in detail the recent studies on methods of real-time forecasting for near-field tsunamis based on either offshore tsunami data or onshore real-time GNSS data. Tsushima et al. (2014) improved near-field tsunami forecasting based on offshore tsunami data soon after an earthquake by incorporating real-time GNSS data (tFISH/RAPiD). The retrospective application to the 2011 Tohoku-Oki Earthquake demonstrated the ability to rapidly predict tsunamis approaching the near-field coastal areas widely and impulsive tsunamis affecting specific sites.

Kato et al. (2011) and Terada et al. (2011) introduced their recent development of GPS buoy system for detecting tsunami before its arrival to the nearby coast. They showed that their system enabled to record tsunami caused by the 2010 Maule Earthquake (Mw 8.8), Chile, and the 2011 Tohoku-oki earthquake (Mw 9.0). In the latter case, they indicated that the tsunami at the Tohoku-oki earthquake was observed in real-time and was used to revise the tsunami warning issued by the Japan Meteorological Agency. Yamamoto et al. (2014) showed that the GPS buoy system is further developed to deploy the system for much far offshore for more effective use for tsunami disaster mitigation. They showed that a newly implemented software allows real-time precise point positioning with ambiguity resolution (PPP-AR) and can attain a few centimeter accuracy in positioning of moving platform. They also tried satellite transmission of the data successfully, which enables to deploy GPS buoy for much farther from the coast, say more than 1000km. Kato (2013) reviewed Japanese research activity since the advent of the GPS technology for geodetic applications, and he extended that the next "dream" of GPS research in Japan could be the dense GPS buoy array in the western Pacific.

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3.4 SAR

Japan Aerospace Exploration Agency (JAXA) launched the Advanced Land Observing Satellite (ALOS) with L-band SAR (PALSAR) on Jan 24, 2006. Before stopping its operation on 12 May, 2011, ALOS acquired valuable images of the 2011 off the Pacific coast of Tohoku earthquake (the 2011 Tohoku-Oki earthquake hereafter), which is fully described in Section 6. JAXA launched next satellite

ALOS-2 on 24 May 2014, carrying PALSAR-2, an improved Phased Array type L-band Synthetic Aperture Radar. The spatial resolution of PALSAR-2 increased 3 to 10 times from that of PALSAR. The revisit time is reduced from 46 days to 14 days (best effort). ALOS-2 also equips left-looking mode in addition to the conventional right-looing mode. ALOS-2 succeeded to detect the surface deformation related to several disasters (e.g., Eruption of Mt. Ontake, Damaging earthquake in Nagano Prefecture, Japan), which is described in Section 6.

GSI has routinely processed ALOS PALSAR data, which is briefly summarized below. Yamanaka et al. (2011) revealed huge displacement caused by the 2011 Tohoku-Oki Earthquake using InSAR analysis combined with GEONET. Sato et al. (2014) detected landslides triggered by the 2011 Tohoku-Oki Earthquake from the InSAR results. Noguchi et al. (2011), Yamanaka et al. (2013), and Morishita et al. (2013) used an InSAR stacking method or InSAR time series analysis to detect a slow slip or ground subsidence.

Ozawa and Ueda (2011) proposed an advanced InSAR time series analysis using interferograms of multiple-orbit tracks. In a case study on Miyake-jima, Japan, they found uplift along the west coast and subsidence with contraction around the caldera. The speed of the uplift was temporally constant, but subsidence in the caldera bottom decelerated from 2009.

Kobayashi et al. (2014) presented a topic about development of a tool for reduction of atmosphere-related noises in an InSAR image using a numerical weather model and showed the effectiveness and the limitation for practical use.

Sri Sumantyo et al. (2012) used the long-term consecutive differential interferometric synthetic aperture radar (SAR) technique with the ALOS/PALSAR and JERS-1/SAR to measure the volume change during land deformation of the subsidence of Bandung city, Indonesia.

Furuya (2011) reviewed the principles of SAR interferometry in a very introductory fashion. Kobayashi et al. (2011) reviewed a SAR pixel offset technique in the context of an observation for local large ground surface displacement and evaluated the robustness of measuring large crustal deformation, the capability of measuring azimuth component, the insensitivity to change of scattering characteristics.

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3.5 Other Techniques

Ohkubo and Tanaka (2012) developed a novel technique of density profiling by counting cosmic-ray muons that travel through a target. The muon radiography and classical gravimetry are both sensitive to target density while complementary to each other in several aspects. ERI estimated magma head height in a volcano by analyzing time series of absolute gravity while constraining conduit dimensions with the muon radiography. Nishiyama et al. (2014) developed an integrated processing method for muon radiography and gravity anomaly data for determining the 3-D density structures of volcanoes with a higher spatial resolution than is possible by conventional gravity inversion. They applied the method to a volcano, Showa-Shinzan lava dome, Hokkaido, Japan and derived the detailed shape of a vent beneath the dome and detected the presence of solidified dense lava near the top of the dome.

Liu et al. (2012) introduced their recent research of applying a new method of ultra-high resolution multiplexed fiber Bragg grating sensor for crustal strain monitoring. They are making an experiment at the Aburatsubo crustal movement observatory of Earthquake Research Institute, The University of Tokyo. The results are sufficiently consistent with conventional silica-tube strainmeters.

Kokubo (2013) performed theoretical considerations about the response of the tiltmeters. The examples show the importance of understanding that rapid apparent changes of the 1-sps tiltmeter records are always caused not by tilts, but by translational motions for these models, and their polarizations appear in opposite directions to tilt changes for Mogi's model in particular.

Arai et al. (2011) reported the first unequivocal observations of atmospheric boundary waves associated with the tsunami caused by the 2011 Tohoku-Oki Earthquake. Potential usefulness of an observation network of atmospheric pressure is discussed regarding the improvement of the tsunami warning system.

Murayama et al. (2011) reported the development of a low-cost, portable observation system of infrasound. The system consists of the nano-resolution pressure transducer Model 6000-16B manufactured by Paroscientific Inc., USA and pressure hoses (flexible polyvinyl chloride product) for reducing wind noise. Field tests revealed that the system compares well with the CTBT monitoring system using MB2005 microbarographs.

Doi et al. (2012) developed a GPS data remote retrieval system consisted of GPS logger, a ZigBee communication and wireless LAN. They reported ground GPS data retrieval tests using a small unmanned aerial vehicle as well as ground based retrieval test from GPS buoy on an Antarctic sea ice.

Matsushima et al. (2012) developed a hybrid technology for a detailed mapping of surface temperature distribution over active volcanoes combining a portable thermometric instrument and a positioning instrument. They conducted an aerial thermographic survey over active volcanoes and demonstrated its usefulness.

GSI investigated the cause of seasonal fluctuations observed in repeated leveling results around Omaezaki area in Shizuoka prefecture. As a result, the presence of systematical errors was confirmed. They are caused by temperature changes of a level staff in short period associated with the change in irradiation conditions of sunlight, large variations of collimation line of electronic level associated with the temperature change during daylight, the interaction between the gradient tilt change of a level tripod top plate caused by direct sunlight to a leveling tripod, and the hysteresis characteristic of the compensator installed in a level.

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4. General Theory and Methodology

Large-scale crustal deformation over a wide area of eastern Japan was detected by GEONET following the 2011 off the Pacific coast of Tohoku Earthquake occurred on March 11, 2011. Since it was assumed that positions of the control points for public surveys, such as GEONET stations, triangulation stations, and leveling bench marks in a wide area were greatly moved and the coordinates of Survey Results for survey use were not consistent with the coordinates of actual positons, GSI suspended the publication of the Survey Results and announced it publicly on March 14, 2011.

In order to conduct the activities for reconstruction in the disaster area, it was strongly required immediate revision of the Survey Results. However, large postseismic deformation had continued widely after the earthquake, and it was difficult to determine the precise position of the control points as Survey Results. Even if the Survey Results were revised immediately after earthquake, the actual position of the control points moved continuously, and the revised Survey Results could be ineffective in a short time. Therefore, GSI examined the most appropriate date to revise the Survey Results by estimating the amount of postseismic deformation after the earthquake, based on the observation data of GEONET stations. The Survey Results of GEONET stations were recalculated from the VLBI observation data on May 10 and the rapid solutions of GEONET stations in May 23-25, and published on May 31, 2011.

In the area where the publication of Survey Results was suspended, geodetic surveys were conducted at 1,867 triangulation stations, and the Survey Results of the other stations (about 41,000) were recalculated based on the data of the geodetic surveys because it was impossible to conduct the surveys at all of the triangulation stations in the short time. In the calculation, GSI created parameters to correct the amount of the crustal deformation on horizontal coordinates or elevation using the results of the geodetic surveys at GEONET and triangulation stations. The parameters could not be applied in the revision of Survey Results of bench marks that require elevation accuracy of 0.1mm to 1mm, because the accuracy of the parameters for elevations was more than 10cm. Therefore, high-precision leveling was conducted in Tohoku and Kanto districts. The total length of the observed leveling route was about 3,700 km. Eventually, the revised Survey Results of the triangulation stations and leveling bench marks were published on October 31, 2011 (Hiyama et al., 2011).

Kuroishi (2013) applied the semi-discrete wavelet transform to geodetic data in one-dimensional (time series) and two-dimensional (geographically distributed) form for isolating localized signals and evaluated the performance by means of coherency analysis.

Doke et al. (2014) reported the method to calculate spatially homogeneous strain field from GNSS velocity field by using Nearest Neighbor method with examples of Izu Collision Zone and Hakone Volcano.

Fukushima (2012a) pioneered a novel method to compute Associated Legendre Functions (ALF) of ultra-high degree/order free from the underflow/overflow problems by extending the exponent of floating point number to a 32/64 bit integer. Fukushima (2012b) developed a new method to compute the finite difference of ALF, which is useful in the precision computation of the integral of ALF, without cancellation problems. Fukushima (2012c) extended the method of the exponent extension of floating point numbers so as to compute the derivatives of ALF of ultra-high degree/order free from the underflow/overflow problems. Fukushima (2014a) augmented the method of the exponent extension of floating point numbers in order to compute the integrals of ALF of ultra-high degree/order free from the underflow/overflow problems.

Fukushima (2012d) invented a parallel algorithm to compute the gravitational field of the Earth acting on artificial satellites. Fukushima (2013) established a recursive method to compute the oblate spheroidal harmonics of the second kind and their derivatives, which are needed in developing the oblate spheroidal harmonic expansion of the external gravitational field of the Earth. Fukushima (2014b) applied the recursive method to compute the spheroidal harmonics of the second kind and their derivatives to those related to prolate spheroids, which are suitable to describe the gravitational field of peculiar asteroids like Eros.

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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 32 fundamental gravity stations (FGSs) and 69 first-order gravity stations (GSs). In addition, GNSS 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 55 per cent of the network stations for GNSS and 69 per cent for leveling.

GSI carried out absolute gravity measurements at 20 FGSs with FG5 absolute gravimeters (Micro-g LaCoste Inc.: Nos. 104, 201 and 203). During the period concerned, GSI established a new FGSs, Tsushima in 2013, and the total number of FGSs amounts to 32.

5.2 Absolute Gravimetry

To examine the possible change of gravity associated with the 2011 off the Pacific coast of Tohoku Earthquake, GSI made absolute gravity measurements at Sendai, Hachinohe, Esashi and Hirosaki FGS from June 2011 to June 2012. GSI also made relative gravity measurements at 32 GSs in the area. Large gravity changes are detected throughout the observed area. The maximum gravity increase is 93 microgals at Iwaki GS with respect to the value in February 2005.

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ, AIST) carried out absolute gravity measurements for various purposes including (1) groundwater monitoring at the Hachijojima geothermal field (Sugihara et al., 2011) , (2) the gravity monitoring at CO2 sequestration field by using A10 with gPhone in Utah, USA (Sugihara et al., 2012; 2013a) and by using FG5 with iGrav SG in Texas, USA (Sugihara et al, 2013b; 2014), (3) calibration of FG5 in Tsukuba mountain, and (4) calibration of superconducting gravimeter at Matsushiro in 2013, 2014 and Kamioka in 2013.

Fukuda et al. (2011) employed a field absolute gravimeter Micro-G LaCoste Inc. A10-017 for detecting gravity changes associated with various phenomena, for instance, geothermal fluid monitoring, groundwater changes and land subsidence. They reported the results of the surveys, and concluded that A10 was a powerful tool for these purposes and would be more extensively used in the various studies.

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5.3 Gravimetry in Antarctica

An absolute gravity measurement had been carried out using an absolute gravimeter FG-5 #210 at IAGBN(A) site in Syowa Station, Antarctica in January 2012. This was the fifth measurement at the site using FG-5 type gravimeter. Higashi et al. (2013) reported the obtained gravity value and gravity change rate.

Doi et al. (2013) reported field absolute gravity measurements on an outcrop rock as well as relative gravity measurements and height measurements in Langhovde, east Antarctica conducted by the 53rd Japanese Antarctic Research Expedition in 2012. Kazama et al. (2013) obtained the absolute gravity value of 982,535,584.2 ± 0.7 micro-Gal at Langhovde (East Antarctica) on 3 February 2012, using the portable absolute gravimeter A10. This was the first absolute gravity measurement on the Antarctic Continent for the Japanese Antarctic Research Expedition.

As an activity of the 56st Japanese Antarctica Research Expedition, GSI conducted absolute gravity measurements with FG5 (Nos. 203) at Syowa Station (IAGBN No.0417) and its backup site, nearly continuously for one month period from January 6, 2014 to February 5, 2015. The gravity values obtained at these two sites agree within 2 microgals with those obtained with the same meters in 2010, indicating absence of uplift of land.

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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 9 times during 2011 to 2014, 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 and Earthquake Research Institute (ERI), The University of Tokyo, conducted absolute and relative gravity measurements at the Izu-Oshima volcano in October 2012. ERI made absolute measurements both at the edge of caldera and foot of the volcano, and then they made relative measurements at 49 sites covering the volcano. The gravity values increase up to 30 microgals around summit crater and decrease up to 40 microgals at northeast part of the caldera with respect to the value in October 2008. The results were reported to the Coordinating Committee for the Prediction of volcanic eruption, Japan.

ERI, Tohoku University and Hokkaido University carried out continuous absolute gravity measurements in the vicinity of Shinmoe-dake volcano, which commenced erupting in late January 2011. Okubo et al. (2013) found that 20 of 24 eruptive events are associated with precursory short-term gravity decreases occurring over 5-6 hours followed by quick recoveries lasting 1-2 hours. The gravity changes and crustal deformation observed during the one year period are well explained by inflation of a magma reservoir at a depth of 9 km and intrusion at shallower depths of a dike.

ERI and Disaster Prevention Research Institute (DPRI) performed absolute gravity measurements at Sakurajima volcano, Japan, from April 2009 through January 2011 (Watanabe and Matsumoto, 2013). After correcting for hydrological disturbance, the observed variations in gravity can be divided into 5 separate phases, which are closely linked to the eruptive activity at Showa crater. In fact, excellent correlations are found among the records of absolute gravity, ejected weight of volcanic ash, ground tilt, and infrasound air shock amplitude. The gravity data are transformed into changes in magma head height using a simplified line mass model.

Tanaka et al. (2014) developed a theoretical computation method of postseismic relaxation in a spherical Earth with a 3-D viscosity distribution. By applying the theory to the 2004 Sumatra event, postseismic gravity variations in the GRACE data were explained by afterslip and relaxation caused by

Burgers and Maxwell rheology.

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5.4.2 Gravity Changes Associated with Hydrological Effects

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ, AIST) carried out continuous gravity monitoring using gPhone gravimeters and also carried out the so-called hybrid gravity measurements using FG5 absolute gravimeter and CG-5 relative gravimeter at the Hachijojima geothermal field, Japan (Sugihara et al. 2011; 2012). Tanaka et al. (2013) successfully detected some hydrological gravity responses by using a gPhone gravimeter both belowground (the Mizunami Underground Research Laboratory) and aboveground (the Ontake volcano), and then proposed to detect and correct the responses using multiple gravimeters to study gravity signals from deep within the earth.

Kazama et al. (2012) calculated the gravity changes due to local hydrology using the new one-dimensional hydrological model, and reproduced the superconducting gravity changes obtained at Isawa Fan (Northern Japan) from 2009 to 2010 within about 1 micro-Gal root-mean-square. Kazama et al. (2014) calculated the hydrological gravity changes using the new empirical model, and found that most of the relative gravity change measured at Sakurajima Volcano (Southern Japan) during 2007-2009 can be explained the hydrological effects, not by the volcanic signal.

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5.4.3 Gravity Changes Associated with Isostatic Adjustment

Sato et al. (2011) reevaluated the viscoelastic and elastic responses to the past and present-day ice changes in Southeast Alaska using 91 GPS site velocities to reveal the temporal variations in the uplifting rates, which are considered to be mainly due to the glacier changes after the 1990s. Sato et al. (2012) conduct absolute gravity (AG) measurements at 6 sites in Southeast Alaska since 2006. At two of the 6 sites, IGPP has also conducted the measurements in 1987. Model computations for the unloading effects due to three different time intervals, LGM, LIA and Present-Day indicate that the observations mainly reflect an early stage of viscoelastic relaxation due to the effects after the LIA.

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5.5 Gravity Survey in Japan

5.5.1 General

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ, AIST) conducted gravity surveys in order to prove the brief feature of gravity anomalies in Japan. GSJ, AIST published the digital gravity database (revision of CD-ROM version in 2004) on DVD, which includes gravity measurements data file, gridded gravity anomaly data, Bouguer anomaly maps and free-air anomaly maps (Geological Survey of Japan, AIST, 2013a). GSJ, AIST published two detailed complete Bouguer anomaly maps of 1:200,000 scale, “Gravity Map Series” for Himeji District and Tokushima District as part of the gravity mapping program of Japanese Islands (Geological Survey of Japan, AIST, 2013b; 2013c).

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5.5.2 Hokkaido Area

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ, AIST) carried out sea floor and land gravity surveys along in the coastal area of Tomakomai, Hokkaido in 2012 (Geological Survey of Japan, 2014).

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5.5.3 Honshu Area

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ, AIST) carried out the gravity survey in and around faults area of the April 2011 Fukushima Earthquake (Mj 7.0) at Iwaki, Fukushima (Murata et al. 2013).

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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, AIST) carried out sea floor and land gravity surveys along the northern coastal area of Fukuoka prefecture in 2010 (Geological Survey of Japan, 2013) .

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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, AIST) carried out a gravity survey at the Farnsworth CCS-EOR field in Texas, USA.

5.7 Marine Gravimetry

The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ, AIST) 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 until 2011. After 2012, the survey vessel Hakurei has been used. The cruises during the period from 2011 through 2014 are listed in Table 1. The gravity measurements were conducted using a straight-line sea gravimeter, LaCoste& Romberg SL-2, for the cruises by Hakurei-maru No.2 and a gravimeter, Micro-g LaCoste Air-Sea Gravity System II for the cruises by Hakurei. 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, 2011, 2012a, 2012b, 2012c, 2013, 2014).

Table 1. Cruises for marine gravimetry by the GSJ during the period from 2011 to 2014.

Cruise ID	Cruise Period	Survey Area
GH11	14Jul – 15Aug, 2011	Northern Okinawa Trough
GH12	20Jul – 30Jul, 2012	Around Okinoerabu-jima Island of Okinawa Islands
GH13	20Jul – 30Jul, 2013	Around Tokuno-shima Island of Okinawa Islands
GH14	10Aug – 20Aug, 2014	Around Amami-oshima Island and Kikai Island of Okinawa Islands

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Geological Survey of Japan, AIST (2012b): Geological Map of the Vicinity of Teuri Island, Marine Geology Map Series, no. 75 (CD).

Geological Survey of Japan, AIST (2012c): Geological Map of Hidaka Trough, Marine Geology Map Series, no. 77 (CD).

Geological Survey of Japan, AIST (2013): Geological Map of West of Cape Soya Misaki, Marine Geology Map Series, no. 78 (CD).

Geological Survey of Japan, AIST (2014): Geological Map Offshore of Cape Erimo, Marine Geology Map Series, no. 83 (CD).

5.8 Data Handling and Gravity/Geoid Maps

Kuroishi (2012) developed a new method for smoothing tide gauge data which is proposed to monitor temporal changes of mean sea level combined with vertical land motion at the tidal stations by using the semi-discrete wavelet transform. Kuroishi (2013) determined sea surface dynamic heights around Japan from a combination of a regional geoid model, tidal records, and GPS/leveling data at the coast and on isolated islands, and compare them with an oceanographic model. Kuroishi (2014) determined geocentric positions of mean sea level at the tidal stations by combining the smoothed tidal heights with ellipsoidal heights at adjacent GNSS stations. The mean bias to leveled mean sea level heights was about +26.9 cm with the standard deviation of 7.3 cm.

Odera et al. (2012) have developed a high-resolution geoid model covering the four main islands of Japan from EGM2008 and terrestrial gravity data. They employed the Stokes-Helmert scheme in a modified form. In comparison with the previous geoid model for Japan (JGEOID2008), there is a slight improvement in the standard deviation from ±8.44 cm to ±8.29 cm. Odera and Fukuda (2013) evaluated the performance of the Gravity field and steady-state Ocean Circulation Explorer (GOCE) the geopotential models (GGMs) Release 1-3 over Japan. They showed that the accuracy of the geoid over Shikoku island could be improved by using the GOCE GGMs. Odera and Fukuda (2014) developed an improved high-resolution gravimetric geoid model covering the four main islands of Japan (Hokkaido, Honshu, Shikoku, and Kyushu) from EGM2008, GOCO02S/EGM2008, and terrestrial gravity data. They employed EGM2008- and GOCE-related GGMs based on their earlier evaluation of the performance. In comparison with the previous geoid model, the new model shows an improvement in the standard deviation from ±8.3 to ±7.5 cm.

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5.9 Hybrid Geoid Model

GSI developed a new hybrid geoid model of Japan, "GSIGEO2011", which was created by fitting a high-resolution gravimetric geoid model for Japan, "JGEOID2008", to GNSS/leveling geoid undulations at 971 sites by the Least-Squares Collocation method. The model reproduces geoid heights at the GNSS/leveling sites with the consistency of a standard deviation of 1.8 cm. The consistency is greatly improved compared with the former hybrid geoid model of Japan, "GSIGEO2000, and by utilizing the model to convert GNSS-derived three-dimensional positions to orthometric heights, GNSS survey can determine orthometric heights at the same precision as third-order leveling surveys (Miyahara et al., 2014).

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5.10 Space Gravimetry

5.10.1 Lunar and Planetary Gravimetry

Goossens et al. (2011a) developed a lunar gravity field model up to degree and order 100 in spherical harmonics named SGM100i from SELENE and historical tracking data, with an emphasis on using same-beam S-band differential VLBI data obtained in the SELENE mission. Goossens et al. (2012) presented a local lunar gravity field model over the South Pole-Aitken (SPA) basin on the far side of the Moon by estimating adjustments to a global lunar gravity field model using SELENE tracking data. The resolution of the model is equivalent to degree and order 150. Yan et al. (2012) combined Chang'E-1 tracking data with SELENE and historical tracking data to develop a lunar gravity field model named CEGM02. The higher orbit altitude (200 km) of Chang'E-1 contributed to better estimation of long-wavelength component of the lunar gravity field.

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5.10.2 Satellite Gravity Missions

Yamamoto et al. (2011) compared the Gravity Recovery and Climate Experiment (GRACE) gravity change trend and the Ice, Cloud, and land Elevation Satellite (ICESat) elevation change trend from October 4, 2003, to March 21, 2008, to evaluate four glacial isostatic adjustment (GIA) models (ICE-5G, IJ05, ANT5 and ANT6) at six selected areas over West Antarctica. They showed that the mass trend predicted by IJ05 GIA model is the most preferable to explain surface mass trends over these areas.

Ogawa et al. (2011) investigated quadratic terms in the time variable gravity in land area from GRACE satellite gravimetry, and found that they reflect the linear changes of the land water flux, mainly precipitation. Matsuo and Heki (2012) found a significant correlation between wintertime hydrological mass anomaly in Northern Hemisphere and Arctic Oscillation (AO) which is one of a dominant climate mode in winter. Using GRACE data, they showed that positive and negative AO enhance wintertime precipitation in the high and middle latitude regions in Northern Hemisphere. Matsuo and Heki (2013) investigated recent ice losses in small glacier systems of the Arctic Islands, i.e. Iceland, Svalbard, and the Russian High Arctic, from satellite gravity data by GRACE. In the period 2004-2011, the total ice loss rate of these regions were estimated to be about 20 gigatons per year, about twice as fast as the average rate over 40 years interval before the studied period. Matsuo et al. (2013) detected the acceleration of ice mass depletion in Greenland for the period 1991-2011 from the low-degree gravity field up to degree and order 4 derived from the Satellite Laser Ranging (SLR) data. It was revealed that Greenland mass trend was nearly balanced in 1990s and shifted to decrease in 2000s. Matsuo and Heki (2014) re-estimated the glacial ice loss rates of the Himalayas and major mountain belts in central Asia using updated and extended GRACE data, and obtained the total ice loss rate of 40 gigaton per year in 2003-2009 and 27 gigaton per year in 2003-2012.

Matsuo and Heki (2011) detected coseismic gravity changes due to the 2011 off the Pacific coast of

Tohoku earthquake (Mw 9.0) from satellite gravimetry by GRACE, and examined the observed gravity changes through model calculation. The observed gravity changes were dominated by decrease over the back-arc region, and were well explained by coseismic crustal dilatation of the landward plate.

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5.11 Superconducting Gravimetry

Continuous observation by a superconducting gravimeter OSG#058 was started on January 7, 2010 at Syowa Station, Antarctica. Ikeda et al. (2012) showed observed seismic waves induced by the Great East Japan Earthquake occurred on March 11, 2011.

The superconducting gravimeter CT-36 was moved from the Inuyama station, Aichi, to the Ishigakijima station, Okinawa in 2012. Ikeda et al. (2013) reported the refurbishment of the gravimeter that was made prior to the movement at Tsukuba, Ibaraki. Instrumental performances of the gravimeter were also investigated.. The Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ, AIST) carried out continuous gravity monitoring using iGrav superconducting gravimeters at Farnsworth, Texas, USA (Sugihara et al. 2013b; 2014) for development of a monitoring method for both lowering costs and increasing the safety in CO_2 sequestration.

Imanishi et al. (2013) investigated the budget of the groundwater that affects the gravity observations at Matsushiro underground station. It was shown that translatory flow of underground water in the bedrock is the dominant process, and the empirical model of Imanishi et al. (2006) was given a qualitative explanation.

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5.12 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 5 stations distributed in the country during 2011-2014. 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. Ueda et al. (2013) reported magnetic charts for epoch 2010.0, which was obtained by applying the models for the observation data of the observatories and the first-order geomagnetic stations in Japan from 1970 to 2010.

Using the dense network of Global Navigation Satellite System (GNSS) array in Japan, Maeda and Heki (2014) succeeded in 2-dimensional mapping of midlatitude sporadic-E layers whose morphology and dynamics have been ambiguous so far.

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6. Crustal Deformation

6.1 Secular Movements

6.1.1 Plate Motion

Nishimura (2011) clarified significant eastward velocity at the GEONET GNSS stations in the Izu Islands relative to stable Philippine Sea plate. The velocity successfully rigid rotational movements of the Izu forearc, which suggests contemporary back-arc spreading in the Izu Islands arc. Yoshida et al. (2012) focused crustal deformation in recent years in southern Kanto revealed by the GNSS, which is supposed to be caused by the subduction of the Philippine Sea plate, differs apparently from the displacements at the Kanto earthquake. They pointed out a possibility that other types of fault motion different from that of the 1923 Kanto earthquake may occur in the future or might have occurred in the past.

Heki and Mitsui (2013) considered the sudden post-2003 increase of landward interseismic movements of the GNSS stations in northern Tohoku District as the manifestation of the acceleration of the Pacific Plate slab subduction caused by the loss of coupling by the 2003 Tokachi-oki earthquake (Mw 8.0).

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6.1.2 Interseismic Motion

Java is located along Sunda trench but there is no historical record of meagthrust earthquake. Hanifa et al. (2014) studied recently installed continuous GPS data and pointed out that plate interface south of west Java has significant interpolate coupling and has a potential to generate great earthquakes over Mw 8.6.

Duong et al. (2013) studied crustal deformation around active fault zones in northwestern Vietnam with campaign GPS observation. They identified the northwestern Vietnam is not a part of the Sundaland plate or the South China block, but located in a transition zone between these two tectonic blocks.

Seismic potential of the active faults in northwestern Vietnam were estimated based on GPS data.

Crustal deformation along subduction zones is considered to reflect spatial extent and degree of interplate locking. But it is also biased by mechanical interaction between locked and unlocked parts on the plate interface, and is obscured by the elastic response of the lithosphere. Hirai and Sagiya (2013) conducted numerical experiments to clarify these points quantitatively, and obtained empirical relationship between apparent and actual locking percentage.

Sato et al. (2013a) revealed the spatiotemporal variation of interplate coupling off Miyagi and Fukushima Prefectures, northeastern Japan, by observing seafloor movements for about 9 years before the the 2011 off the Pacific coast of Tohoku earthquake (the 2011 Tohoku-Oki Earthquake hereafter) with the GPS/acoustic technique.

Ochi and Kato (2011) used GPS and leveling data in the Tokai region, central Japan, for the period of 1996-2000 to estimate plate coupling along the subducting Philippine Sea plate. The vertical data show that the most strongly coupled portion of the subduction interface is concentrated beneath Omaezaki Cape, while the horizontal data show strongest coupling in the shallower region of the subducting plate interface.

Ponraj et al. (2011) examined slip distribution beneath the Central and Western Himalaya using campaign-mode GPS data to propose a model for the interplate coupling of the plate boundary, where the locking depth appears to be deeper in the Central Himalaya and shallower in the Western Himalaya.

Interseismic motion was also detected in and around the active faults. Using InSAR analysis, Kaneko et al. (2013) detected interseismic creep siganls at the north Anatolican Fault, Turkey. Yoshida et al. (2011) suggested subsidence at the eastern side of the Tanna fault represents a tectonic movement whereby the Manazuru block squared by the Tanna fault, Hirayama fault, Kannawa fault, and Kozu-Matsuda fault performs buoyant subduction. Ohzono et al. (2011) studied detailed crustal deformation pattern around the Atotsugawa Fault zone in central Japan and construct a kinematic block-fault model to describe the ongoing crustal deformation. Imai and Takeuchi (2013) detected stationary crustal movements in the Shin’etsu region by analyzing GEONET GPS data obtained during about three years before the 2011 Tohoku-Oki Earthquake, and suggested the region can be separated into some tectonic provinces by comparing their movement patterns with geological and subsurface information.

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6.2 Transient Movements

6.2.1 Coseismic Movements due to the 2011 Tohoku-Oki Earthquake

Seismic and volcanic activities are very high after the 2011 off the Pacific coast of Tohoku earthquake (the 2011 Tohoku-Oki Earthquake hereafter), and so many papers were published for the last four years. Although it is difficult to categorize related papers, the works directly treat coseismic deformation of the Tohoku-Oki earthquake are listed first.

In response to the 2011 Tohoku-Oki Earthquake, Sagiya et al. (2011) discussed possible causes of the failure in making successful forecast and propose countermeasures to improve the existing problems.

Sato et al. (2011a) detected seafloor movements associated with the 2011 Tohoku-Oki Earthquake

(Mw 9.0) directly above the focal region by the GPS/acoustic observation. They detected the displacement of 24 meters toward east-southeast and nearly 3 meters of vertical uplift just above the epicenter. Geodesy and Geophysics Office, Hydrographic Survey Division (2012) reported coseismic displacements detected by the GPS/acoustic seafloor geodetic observation, the GPS positioning and the SLR measurements. Y. Ito et al. (2011) report a coseismic uplift of 5 m with a horizontal displacement of more than 60 m. The uplift was measured by an ocean-bottom pressure gauge installed before the earthquake on a frontal wedge, which formed an uplift system near the Japan Trench.

Suito et al. (2011) reported a coseismic deformation and fault model based on GEONET (GNSS Earth Observation Network Systems) along the time line of the GSI operations. Nishimura et al. (2011) clarified coseismic displacements of the mainshock, the largest foreshock, and the large aftershocks using kinematic analysis of GEONET data and estimated their rectangular fault models. GNSS time-series suggest no accelerated deformation just before the main-shock. Ozawa et al. (2011) estimated the coseismic and postseismic slip and found out that coseismic slip is very large up to around 30 m and large afterslip area is located down-dip of the coseismic slip area. Miyazaki et al. (2011) inferred coseismic slip distributions for the mainshock, its foreshock in off-Iwate area, its large aftershocks in off-Iwate and off-Ibaraki areas, and transient slip between the foreshock and mainshock. T. Ito et al. (2011) analyze geodetic observation data to estimate coseismic and early postseismic fault slip distribution on the Pacific plate interface. The maximum slip and the moment magnitude of the main shock are about 60 m and Mw 9.0, respectively. Takahashi (2011) illustrated coseismic strain and stress changes using nationwide GNSS network data and found that released strain corresponded to 225 to 400 years of strain accumulation. Iinuma et al. (2011) estimated the coseismic slip distribution based on the terrestrial GPS observation data to reveal that the ruptured areas of the earthquakes off Miyagi Prefecture in 1978 and 1930s (M ~ 7.5) again ruptured during the 2011 Tohoku-Oki Earthquake. Iinuma et al. (2012) estimated the coseismic slip distribution based on terrestrial and seafloor geodetic data. The result revealed that an extremely large (>50 m) slip occurred in a small area (about 40 km in width and 120 km in length) near the Japan Trench. Ikuta et al. (2012) investigated coseismic slip distributions and interseismic couplings prior to the earthquake. They inferred that a small locked area suppressed the effective slip deficit in surrounding area before the megathrust earthquake. Nishimura et al. (2012, 2014) analyzed geodetic data including leveling and sea level over the past century and found nearly constant subsidence with a rate of 5 mm/yr along the Pacific coast in the central Tohoku region before the 2011 Tohoku-Oki Earthquake, whereas the long-term uplift is suggested by geomorphologic studies. The coast also subsided at the 2011 Tohoku-Oki Earthquake. This paradox may be resolved by the postseismic uplift of the 2011 Tohoku-Oki Earthquakes.

Shimada et al. (2011) shows the ALOS emergency observation and the results at the event of March 11 2011. From 36 acquisitions, they detected the large-scale changes of the Tohoku area by using the DinSAR of PALSAR and AVNIR-2’s change detection. Hashimoto et al. (2011) shows the deformation pattern of the Tohoku area caused by the 2011 Tohoku-Oki Earthquake using the PALSAR interferometry.

Kobayashi et al. (2011a) detected the coseismic deformation by InSAR analysis using ALOS/PALSAR data and demonstrated that an InSAR analysis incorporating GNSS data effectively reduced noise and enabled the prompt and accurate mapping of the ground displacement. Kobayashi (2013) showed the InSAR-derived coseismic deformation and fault models due to the mainshock and the induced inland earthquakes and the spatial distribution of liquefaction inferred from coherence changes.

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6.2.2 Postseismic Deformation due to the 2011 Tohoku-Oki Earthquake

Suito et al. (2011b) reported that some stations had observed postseismic deformation by up to 79 cm for 7.5 months after the 2011 Tohoku-Oki Earthquake. Kimura et al. (2013) approximated this postseismic deformation. Suito et al. (2012) reviewed the coseismic and postseismic deformations and their fault model, and discussed the knowledge we should learn or obtain from this giant earthquake. Munekane (2012) estimated slip distributions of the afterslips and aftershocks sequence and found that each slip occurs in a region adjacent to that of the previous slips in a complementary manner. Fukuda et al.

(2013) estimated the spatiotemporal evolution of afterslip using GPS data and found that the evolution of afterslip is consistent with slip-rate-dependent frictional properties that exhibit less rate-strengthening with increasing slip rate.

Ozawa et al. (2012) estimated the preceding, coseismic, and post seismic slip and found out that the coseismic slip ranges up to around 50m and the preceding slip was occurring before the earthquake. Mitsui and Heki (2013) investigated a very early phase of postseismic deformation. They proposed a scaling relation between early afterslip velocity and mainshock magnitude. They also suggested that tsunami-induced coastal subsidence prior to the tsunami arrival could be detected by on-land GNSS.

Watanabe et al. (2014) detected postseismic movements just above the source region of the 2011 Tohoku-Oki Earthquake. Their results were consistent with effects predicted from viscoelastic relaxation in the upper mantle, providing definitive evidence of its occurrence. Sun et al. (2014) revealed that short-term deformation near the rupture zone is mainly caused by not afterslip on the plate boundary fault, but viscoelastic relaxation based on the seafloor landward displacements that were detected based on the observations made immediately after the main shock.

By investigating the time-variable gravity time series from GRACE before and after the three M9 class megathrust earthquakes, Tanaka and Heki (2014) found that the postseismic gravity changes are composed of two components with different polarity and time constants. They possibly correspond to afterslip (decrease with timescales of a few months) and viscoelastic relaxation of the upper mantle (increase with timescales of a few years).

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6.2.3 Crustal Movement Triggered by the 2011 Tohoku-Oki Earthquake

Geodetic works revealed the detail of large aftershocks and some earthquakes clearly triggered by the 2011 Tohoku-Oki earthquake (Mw 9.0).

Ohta et al., (2011) proposed a coseismic fault model for the 2011, April 7, intraslab earthquake (M7.1) in northeastern Japan based on data from a dense GNSS network. The model suggests that the 2011 Tohoku-Oki Earthquake deepened the depth of the stress-neutral plane between the double seismic zone in the subducting slab. Fukushima et al. (2013) obtained surface deformation associated with the 11 April Iwaki earthquake (M_w 6.6) using InSAR analysis. They identified normal-fault-type surface ruptures along four different active faults, and estimated the slip distribution on each fault plane from InSAR images. Kobayashi et al. (2012a) detected the complicated coseismic deformation due to the 2011 Fukushima Hamadori earthquake by InSAR analysis using ALOS/PALSAR data and derived the fault model consisting of three faults with nearly pure normal-fault motions on west-dipping planes with a moderate dip angle. Ito and Takeuchi (2013) detected characteristic crustal movements caused by the Nagano-ken Hokubu earthquake by analyzing GEONET GPS data, and showed that the movements can be explained by not only fault motion of the main shock but growth of the Matsunoyama dome due to this earthquake.

Harada et al. (2011) investigated of what the assumed fault planes in and around the Kanagawa Prefecture were influenced because of the 2011 Tohoku-Oki Earthquake. The influence of this earthquake on each assumed fault planes is evaluated by calculating distribution of static stress change (ΔCFF). Harada et al. (2012) investigated the spatial distribution, temporal change and some statistical features of the swarm activity in Hakone volcano after the 2011 Tohoku-Oki Earthquake, and suggested that the swarm activity was induced by the sudden increase of static stress caused by the earthquake.

Ohzono et al. (2012) evaluated an anomalous crustal strain in Tohoku region, northeastern Japan associated with a coseismic stress change of the 2011 Tohoku-Oki Earthquake. This anomaly reflects the locations of inhomogeneous subsurface structure such as strain concentration zone during the interseismic period. With InSAR analysis, Takada and Fukushima (2013) found that five volcanic areas in northeast Japan subsided in response to the extensional stress change caused by the 2011 Tohoku-Oki Earthquake (M_w 9.0). GNSS data demonstrate that the surface subsidence took place almost instantaneously. They pointed out that deformation of hot and weak regions beneath each volcano caused the surface subsidence. Ozawa and Fujita (2013) investigated crustal deformation associated with the 2011 Tohoku-Oki Earthquake and also found local deformations around the Akita-Komagatake, Kurikoma, Zao, Azuma, and Nasu volcanoes. They suggested that coseismic extensional deformation concentrates in the soft medium under a volcano (e.g., magma and its surrounding rock) and that this deformation has caused local deformation with subsidence. Through InSAR analysis, Takada and Fukushima (2014) discussed similarities between the volcanic subsidence triggered by the 2011 Tohoku-Oki Earthquake and that by the 2010 Maule earthquake in Chile (M_w 8.8). A finite element modeling demonstrates that a weak region with elliptic shape under extensional stress increase causes larger surface subsidence than that with spherical shape.

By using ALOS L-band SAR interferomety Murakami et al. (2013) revealed that the 2011 Tohoku-Oki earthquake triggered an episodic sliding motion of a large ground land block with kilometers size on a relatively flat topography covering over an old buried caldera. They infer that a layer of lacustrine origin at the bottom of the caldera provided a sliding surface. They also argue that earthquakes in the past repeatedly trigged similar sliding motion bringing the progressive weakening of the layer.

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6.2.4 Coseismic Deformation: General

Maruyama et al. (2011) detected many fault traces associated with the 2008 Iwate-Miyagi Nairiku earthquake, NE Japan, by airborne LiDAR(Light Detection and Ranging)-derived DEM and geologic field survey, and found that these ruptures well coincide with areas of large displacement gradients detected by SAR pixel offset technique. Abe et al. (2013) modeled the complex co-seismic deformation signals due to the 2008 Iwate-Miyagi earthquake, NE Japan, using a triangular dislocation element to express the non-planar geometry of the source faults. Kobayashi et al. (2011b) detected the coseismic deformation due to the 2010 Fukushima-nakadori earthquake (Mj 5.7) by InSAR analysis using ALOS/PALSAR data and derived the fault model which reveals that the depth was significantly shallower than that determined by seismic data.

Furuya and Yasuda (2011) detected the co-seismic deformation due to the 2008 Yutian earthquake in northwestern Tibet from ALOS/PALSAR images. As the complex deformation signals indicated a non-planar geometry of the source faults, they provided a non-planar fault model, using a triangular dislocation element. Also, they discussed the tectonic implications for the future activity of the Karakax Fault. Hashimoto et al.(2011) revealed coseismic deformation inconsistent with topography, i.e. uplift of fan-delta and subsidence of mountains, associated with the 2010 Haiti earthquake by the analysis of ALOS/PALSAR images. They also presented slip distribution on a northward dipping plane by 42° with a maximum slip of about 4 m. Tobita et al. (2011) presented a map of the coseismic displacement field of the Yushu earthquake on 14 April 2010 in China by combining ALOS ascending and descending ScanSAR interferograms. The estimated slip distribution on the fault plane has two slip peaks. A significant postseismic displacement was detected. Yokota et al. (2012) have examined the rupture process of the 2010 Yushu earthquake from InSAR and seismic datasets. InSAR images made a significant contribution to constrain a bending fault geometry. Kobayashi et al. (2012b) detected the coseismic deformation due to an inland earthquake that occurred in the southeast of Iran (M 6.5) by InSAR analysis using ALOS/PALSAR data and derived the fault model with nearly pure dextral fault motion with NE-SW-oriented strike. Amrjargal et al. (2013) investigated surface deformations associated with two moderate-sized shallow earthquakes that occurred in the southeastern and northwestern stable regions of Mongolia using analysis of ENVISAT/ASAR and ALOS/PALSAR data, respectively. The interferograms indicate uplift of up to ~1 cm for the Mw 5.2 Hatanbulag composite earthquake (20 July, 2005) and a subsidence of up to ~10 cm for another Mw 5.1 earthquake (19 January, 2008). Huang et al. (2013) analyzed seismic and geodetic data, including GPS and ALOS/PALSAR images, in order to reveal source process of the 2010 Jia-Shian, Taiwan, earthquake. They implied that this event is a reactivation of deep pre-existing geological structure, considering the estimated slip direction and depth. Kobayashi (2014) detected the coseismic deformation due to the 2013 Bohol earthquake in Philippines by applying a pixel offset method with the use of RADARSAT-2 SAR data and derived the fault model with nearly pure reverse-fault motion on north-dipping fault planes.

GSI has processed ALOS-2 SAR data for interferometry and detected surface deformation caused by an earthquake in northern Nagano area, Japan, in 2014. The InSAR results have been published online (http://www.gsi.go.jp/BOUSAI/h26-nagano-earthquake-index.html)

Shestakov et al. (2014) detected horizontal and vertical coseismic displacement of a great deep focus earthquake (Mw 8.3) on May 24, 2013 in the Sea of Okhotsk by GPS measurements. An estimated simple dislocation model based on seismicity and displacement distribution pattern explains almost all the data well.

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6.2.5 Postseismic Deformation: General

Sato et al. (2011b) detected seafloor movements associated with, and subsequent to the 7.2-magnitude earthquake off Miyagi Prefecture on 16 August 2005 by the GPS/acoustic observation. Their data indicated that the strain was partly released by the event and strain accumulation restarted after 1–2 years of the postseismic period.

Takada et al. (2011) detected post-seismic deformation following the 2008 Iwate-Miyagi Nairiku earthquake (M 6.8), NE Japan, by InSAR analysis of ALOS/PALSAR data. Both of the ascending and descending interferograms indicate length change in radar line-of-site (LOS) in and around the focal area of main shock. They proposed preliminary fault models that accounts for the post-seismic deformation. Ohzono et al. (2012) analyzed postseismic deformation after the 2008 Iwate-Miyagi Inland earthquake in Tohoku region, NE Japan. Two-years GPS data indicates the existence of viscoelastic rebound around the focal area. A simple two-layered model, a 19.0-23.5 km thickness of elastic layer and underlying 2.4-4.8E+18 Pa viscoelastic layer, explain the data.

Reddy et al. (2013) investigated possible post-seismic crustal movements after the 2001 Bhuj (or Gujarat) earthquake (Mw7.6) that occurred in the Gujarat district, India. After the earthquake, a research group lead by C. D. Reddy and T. Kato conducted a series of GPS observations. They used data of 2001-2007 and found significant signal of post seismic crustal movements. They suggested that rapidly decaying afterslip and poroelastic mechanisms seem to be responsible for postseismic relaxation in the vicinity of epicenter during the initial period subsequent to the Bhuj earthquake. Postseismic relaxation by viscoelastic flow below the seismogenic zone seems to affect displacements across the entire Bhuj region.

Gunawan et al. (2014) studied GPS data after 2005 in Northern Sumatra, Andaman, and Thailand to estimate physical mechanism of postseismic deformation. Thanks to the unique contribution of reliable vertical signal in northern Sumatra by GPS continuous observation, they propose afterslip and Maxwell viscoelastic relaxation are plausible mechanism. On the other hand, Burgers rheology model failed in reproducing the vertical signal.

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6.2.6 Slow/Silent Deformation

Kato (2011) reviewed the term “slow earthquake”, in which he described the observational samples of slow earthquake (or slow slip event (SSE)) that have been observed worldwide. He also introduced recent ideas on the mechanism of such slow earthquakes (or SSE).

Bartlow et al. (2011) compared the slip evolution of the 2009 Cascadia slow slip event and tremor and found that those events showed clear correlations in space and time.

Ochi and Kato (2013) statically inverted the temporal changes to interplate coupling and long-term aseismic slip in the Tokai Region of central Japan from July 1996 to June 2009 using continuous GPS data and leveling observations, and tested a new interpretation of aseismic slip. Miyaoka and Yokota (2012) developed new method to improve the detection ability of slow slip occurred on the plate boundary. In this method, signal to noise ratio of strain meter is enhanced by stacking these time series data. The long term slow slip event at Tokai Region since 2013 has been detected by this method.

Itaba and Ando (2011) shows the evidence for the triggering of a SSE itself by teleseismic surface waves, which was captured by a new strainmeter network. The triggered SSE occurred on a place on the plate interface where the recurrence time for such events had almost expired, whereas other regions were not triggered.

Kitagawa and Koizumi (2013) observed groundwater-pressure changes due to six short-term slow slip events (S-SSEs) that occurred near ANO in the Kii Peninsula from 2011 to 2013 to develop new tools or techniques to detect S-SSEs along subduction zones. The fault models of these S-SSEs explained the changes in the groundwater pressure. Kobayashi (2013) investigated leveling and sea level data for the period from 1972 to 2009 in the Kii Peninsula, and no unsteady deformation exceeding 3 cm was found. Kobayashi (2014) found a long-term slow slip event from 1996 to 1997 in the Kii Channel. The long-term slow slip event had a moment magnitude Mw 6.7 and a duration of 1 to 1.5 years.

Yoshida et al. (2011) investigated swarm activity and crustal deformation in the Wakayama Plain.

The hypocenters of these swarm earthquakes are very shallow and the b-value is anomalously high. GPS and leveling data indicate expansion and upheaval in this region. These facts strongly suggest that there are hot materials beneath the source region.

Suito et al. (2011a) investigated a sequence of M7-class interplate earthquake and postseismic slips and found that total moment released by these transient slips was much larger than the coseismic ones. These transient processes may help us understand not only the postseismic process but also pre-seismic signals indicating the occurrence of the giant earthquake.

Ozawa et al. (2012) estimated the time evolution of the Bungo slow slip for the past three events in southwest Japan and found out that the aseismic slip occurred near Shikoku Island and moved to a deeper area in the Bungo channel over time. Kobayashi and Yamamoto (2011) investigated leveling and sea level data for the period from 1979 to 2008 around the Bungo Channel and found possible long-term slow slip events around 1980, around 1985-1986, and around 1991.

Ozawa (2014) estimated the time evolution of the 2014 Boso slow slip events in Japan and found out that the aseismic slip occurred off the coast of the Boso peninsula and propagated to inland and southern areas. Hirose et al. (2012) determined fault model of slow slip event (SSE) off the Boso Peninsula, central Japan, in 2011 from National Research Institute for Earth Science and Disaster Prevention (NIED) Hi-net tilt change and GNSS data and showed that this SSE was likely hastened by the stress transfer from 2011 Tohoku-Oki Earthquake (Mw 9.0). Hirose et al. (2014) obtained spatiotemporal slip evolution of the Boso SSEs in 2007 and 2011 by applying time-dependent inversion to NIED Hi-net tilt change and GNSS displacement data, simultaneously. The slip propagates together with the accompanying seismicity, indicating that slip is a major driving process for earthquake swarms. Fukuda et al. (2014) analyzed GPS data to estimate the spatiotemporal evolution of the 2013-2014 Boso slow slip event (SSE), Japan, and found that the SSE consists of an early slow acceleration phase with no accompanying seismicity and a later faster slip phase with local earthquake swarm activity.

Yarai and Ozawa (2013) estimated the time evolution of the Hyuga-nada slow slip events in Japan and found out that the aseismic slow slip events occurred in the afterslip area of the 1996 Hyuga-nada earthquakes, southwest Japan.

Ito et al. (2013) describe two transient slow slip events that occurred before the 2011 Tohoku-Oki Earthquake. The first transient crustal deformation was observed over a period of a week in November 2008. The second had a duration exceeding 1 month and was observed in February 2011, just before the 2011 Tohoku-Oki Earthquake. Ohta et al., (2012b) proposed a coseismic slip and afterslip models of the M7.3 foreshock two days before the 2011 Tohoku-Oki Earthquake based on onshore and offshore geodetic data. They show spatially complementary distributions, and the latter is located at the northward neighbor of the hypocenter of the mainshock.

Ohtani and Itaba (2013) developed a method to estimate fault parameters due to slow slip event. According to a simulation study, it is shown that the method can retrieve the given fault parameters for the case of homogeneous fault slip while the extent of fault is underestimated and the slip amount is overestimated for inhomogeneous slip distribution cases. However, the area where the slip is relatively large and the moment magnitude of the slow slip event are well retrieved.

Kano et al. (2013) developed an adjoint data assimilation method for optimizing frictional parameters in the afterslip area and for predicting the timing of the triggered earthquake related to spatio-temporal evolution of afterslip.

Nishimura et al. (2013) proposed a method to detect of short-term slow slip events using GNSS data and systematically searched the short-term slow slip events along the Nankai Trough. Nishimura (2014) applied the method to GNSS data along the Ryukyu Trench. More than 300 short-term slow slip events were found for ~ 17 years in these regions. Although the SSEs along the Nankai Trough are concentrated in a depth of 30-40 km, those along the Ryukyu Trench distributes heterogeneously with a depth between 10 and 60 km.

A large international project called “Multi-disciplinary hazard reduction from earthquakes and volcanoes in Indonesia” (PI: Kenji Satake of ERI and Hery Harjono of LIPI) was carried out for the period of 2009-2012 under the governmental program of SATREPS (Science and Technology Research Partnership for Sustainable Development) funded by JST and JICA. The GPS research group conducted a number of GPS observation in the Java and Sumatra Islands, Indonesia. Among these projects, Meilano et al. (2012) showed results for the Lemban fault, west Java. They suggested possible slow slip in the lower crust.

T. Ito et al. (2012) inferred the depth of shallow aseismic creep and deeper locked segments for the Great Sumatran Fault using regional GPS Network across northern part of Sumatran Fault. In the northern portion of this fault segment, they inferred aseismic creep down to 7.3 km depth at a rate of 2.0 cm/year.

Applying a time-series analysis technique to ALOS/PALSAR images accumulated during four years, Arimoto et al. (2013) clarified the distribution of ground deformation in the city of Semarang, Indonesia. They found rapid subsidence in the low land, which can be related to extraction of ground water, and subsidence of about 10 mm/yr at a site where subsidence was not recognized before. Hashimoto (2014) analyzed ALOS/PALSAR data of the Kyoto and Osaka areas acquired during four years and revealed ground deformation. He found uplift of about 10 mm/yr in southern Kyoto basin and a belt of subsidence of up to 5 mm/yr along the Arima-Takatsuki Fault zone. He also pointed out that both deformations are limited by active faults.

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6.2.7 Volcanic activities

Yamazaki et al. (2011) investigated strain data near an active volcano, Shinmoe-dake (Kirishima), southwest Japan, before and after the 2011 Tohoku-Oki Earthquake (Mw 9.0). Although activation of the Shinmoe-dake following the large earthquake had been worried by some of local residents, strain data suggested no evidence of such activation. Yamazaki et al. (2013) has been monitored strain variations at a site near the Shinmoe-dake volcano by using extensometers in a horizontal tunnel. They found changes in strain several hours prior to sub-Plinian eruptions of the Shinmoe-dake in January, 2011. Using GPS measurement, Nakao et al. (2013) investigated the source location and volume change before, during and after the highest eruptive activity of Shinmoe-dake volcano, occurring between January 26 and 31, 2011. The source locations during three periods are estimated to be the same, which is 5km to the northwest of the summit at a depth of 8km. Ozawa and Kozono (2011) investigated crater change in the 2011 Shinmoe-dake eruption using spaceborne SAR images. Especially, they estimated that the lava dome grew from the morning of January 29 until January 31 with a constant effusion rate of 88.7 m^3/sec. From the estimated lava effusion rate and lava-covered area, they also estimated that lava viscosity was less than 2.1 GPa·s, suggesting the potential to form a lava flow. Kobayashi et al. (2011) detected pre-/post-eruptive crustal deformation associated with the Kirishima volcanic activity by InSAR analysis using ALOS/PALSAR data and derived a spherical pressure source model. Miyagi et al. (2013) also detected crustal deformations associated with the 2011 eruption of Shinmoe-dake volcano (Kirishima), using DInSAR and GPS measurements. The deformation included pre-eruptive inflation, co-eruptive deflation, and post-eruptive inflation, and the deformation source is located at a depth of 7.5km beneath about 5km west of the Shinmoe-dake crater. Miyagi et al. (2014) detected continuous uplift within the Shinmoe-dake crater and slow subsidence outside the crater after the end of eruption, using DInSAR. This means the subsidence is caused by deflation of a shallow source located beneath the crater, which is a reaction to the extrusion of lava.

Ando (2011) investigated the ground deformation associated with the eruptive activity at Eyjafjallajokull volcano in Iceland using InSAR data. They estimated the pressure sources during the eruptive activity using an elevation-modified Mogi model and an Okada model. Chaussard et al. (2013) processed ALOS PALSAR images in Indonesian and Mexican volcanoes to identify three types of relationships between deformation and activity: inflation prior to eruption and associated with or followed by deflation, inflation without eruption and followed by slow deflation, and eruption without precursory deformation. Pérez et al. (2014) monitored and analyzed crustal deformation associated with volcanic activity in El Hierro, Canary Islands, Spain, by using continuous GPS network. After the major activity in 2011, they detected a new submarine volcanic activity west off El Hierro and GPS data showed clear evidence of westward migration of magma activity.

GSI has processed ALOS-2 SAR data for interferometry and detected surface deformation caused by a volcanic activity at Mt. Ontake, Nagano area, Japan in 2014. The InSAR results have been published online (http://www.gsi.go.jp/BOUSAI/h26-ontake-index.html). Takahashi et al. (2011) analyzed volumetric strain and GNSS data during a strong earthquake swarm in Meakan-dake volcano, Japan, and found transient strain change due to possible volatile migration from deep to shallow. Yoshida et al. (2012) investigated the inflation-deflation process accompanied by changes in seismic activity at Azuma volcano using GPS observations campaigns. They evaluated pressure sources using 3-D displacement components, among which the vertical component was corrected to remove tropospheric and ionospheric inhomogenieties. Kimata et al. (2012) report the vertical deformation derived by repeated precise leveling around the Asama volcano, central Japan which erupted in 2004. They made a model assuming a pressure source beneath the volcano to explain the deformation. They discuss the relationship of the activity history of the pressure source and the 2004 eruption. In Asama Volcano, measuring ground deformation by continuous GNSS measurements, Aoki et al. (2013) suggested that the magma intrusion to a depth of about 1.5 km below sea level occurs at the time of the volcanic unrest. The locations of the intrusion being similar in different unrest, along other evidence, lead them to conclude that the magma pathway is subject to structural controls. Itadera et al. (2013) reported seismicity and crustal movement in Hakone volcano caused by earthquake swarm activity occurred on 2013.

Aoki and Sidiq (2014) measured temporal evolution of ground subsidence due to the eruption of LUSI mud volcano. They found that the subsidence to the west of the main vent, where extensive gas exploration is ongoing, was triggered by the eruption. Kusumoto et al. (2014) observed uplift and subsidence reaching 26 mm and -14 mm in the Murono mud volcano located in the Niigata Prefecture of Japan during June to December 2012 by precise leveling measurements and suggested that overpressure changes of fluid mud in in shallow layers, as its source.

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6.3 Periodic Movements

Mitsui and Heki (2012) analyzed the coordinate time series in the kinematic solutions of high-rate GNSS observations immediately after the 2011 Tohoku-Oki Earthquake (Mw 9.0), and found that they include periodic oscillation signals with lots of frequency peaks corresponding to the normal modes of the solid earth. Tanaka (2014) showed that an approximately 9-year cyclic variations were seen in past crustal movement data and the occurrence probability of historical large earthquakes in Japan. The periodicity is probably related to the weak 8.85-year tide. A hypothetical amplifying mechanism based on a block-plate model was proposed.

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6.4 In-situ Deformation Observations

Ohtani et al. (2012) carried out comparison of strain variations measured by borehole strainmeters with GPS-derived strain to investigate the characteristics of the long-term (over the time scale of several months) measurement of strainmeter. The result shows that there are seasonal variations both in strainmeter and GPS where the amplitudes are consistent each other at some stations, but they are not always in phase; Many stations do not show good agreement between GPS and strainmeter.

Yamazaki (2013) re-analyzed strain data obtained by using extensometers in a shallow tunnel, from which occurrences of slow slip events in an adjacent area had been suggested. Comparison between time series of strain and temperature in the vault clarified that correction of strain data distorted by temperature variations is more difficult than expected.

Koizumi (2013) constructed a system for detecting preseismic changes. It is composed of a long-term observation of groundwater, a poro-elastic theory and the pre-slip model. To apply this system to the Tonankai and Nankai earthquakes, an integrated groundwater observation network is constructed in and around Shikoku and the Kii Peninsula.

Kano et al. (2014) reported that even in crystalline rock the pore pressure change induced by deformation such as barometric pressure change, earth tides, and seismic waves is in agreement with theoretical model derived from the linear poroelastic theory. Pore pressure can be a proxy of stress and/or strain.

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6.5 Sea-level Change and Glacial Isostatic Adjustment

Nakashima and Heki (2013) analyzed the multipath signatures using signal-to-noise ratio of GNSS signals observed at 38 tide-gauge stations in Japan, and derived sea surface height variations. They were accurate to ~30 cm at stations with preferable conditions for GNSS tide gauges. Tanaka et al. (2011) developed a method to compute viscoelastic relaxation for a compressible Earth model. They estimated the effects of compressibility on a present-day global-scale velocity field induced by GIA (Glacial Isostatic Adjustment) and showed that the effects on horizontal motion cannot be neglected when modeling GIA.

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7. Marine Geodesy

Tohoku University had built a seafloor geodetic network composed of GPS/acoustic (GPS/A) seafloor benchmarks and ocean bottom pressure gauges (OBPG) in the rupture area of the 2011 Tohoku-Oki Earthquake about three years before the occurrence of the earthquake. The instruments provided invaluable information indicating pre- co- and post-seismic deformation associated with the earthquake. Taken together immediate GPS/acoustic observations just after the 2011 Tohoku-Oki Earthquake at pre-existing seafloor benchmarks off Miyagi region with past observation, Kido et al. (2011) found westward coseismic displacements up to 31m and 15m, which gave a direct evidence of extremely large slip in the shallow part of the subduction zone associated with the earthquake.

The postseismic deformation patterns of the 2011 Tohoku-Oki Earthquake reported by Sun et al. (2014) was significantly different from the one estimated from the onshore observations. The most striking feature in the offshore geodetic observation was landward motions recorded in the largest coseismic slip area. This observation indicates prevalence of viscoelastic relaxation even in early stage of the postseismic deformation. Twenty GPS/A benchmarks were deployed along the Japan Trench after the earthquake to monitor the postseismic deformation and to clarify comprehensive view of the post-Tohoku earthquake deformation.

Inazu and Hino (2011) investigated pressure data from seafloor cables to clarify mechanical noises in the data due to ambient temperature, and data usefulness, for tsunamis, tides, and lower-frequency phenomena. Tsunamis and tides are well measured with carefully referring the temperature. Lower-frequency variations are contaminated by the temperature noises that worsened with age. Inazu et al. (2012) modeled non-tidal oceanic variations using a numerical ocean model. In-situ oceanic bottom pressure data during the 2011 Tohoku-Oki Earthquake were subtracted by the predicted oceanic variations to show slow vertical seafloor displacements prior to the Mw 9.0 earthquake. Hino et al. (2013) examined ocean-bottom pressure records obtained near the epicenter of the 2011 Tohoku-Oki Earthquake to test whether the earthquake was preceded by substantial precursory crustal deformation. No significant crustal deformation related to preslip was detected in the period of roughly a day before the mainshock.

Ishikawa (2011) reported the way of replacement of the seafloor transponders for GPS/acoustic observation and determined the position offsets between the old and new transponders with enough precision. Ishikawa and Sato (2012) evaluated a new method of estimating the center positions of transponder array via constraining the geometry of transponder array for the precise GPS/acoustic seafloor positioning. Ujihara et al. (2013) proposed a new method applying array constraint analysis for maintaining the continuity of GPS/acoustic observation results between from new and old transponders, and considered the possibility that the number of parallel observations can be reduced. Sato et al. (2013b) evaluated the repeatability of the determined position for the sailing GPS/acoustic observation to be about 2 cm in root mean squares in the horizontal component, significantly better than that for the early drifting observation, using the data acquired for about 3 years since 2008.

Hayakawa et al. (2012) analyzed ocean bottom pressure records (BPR) from 4500m depth off Lutzow-Holm Bay in the Antarctic Divergence Zone collected between December 16, 2004 and February 22, 2008 and found that the GRACE data can account for about 38% of variance of ocean signal observed by the BPR.

Sato and Fujita (2012) reviewed the progress in the GPS/acoustic seafloor geodetic observation by the Japan Coast Guard during the10-year period. Kido (2013) also summarized the past seafloor geodetic observation in the last decade, especially for GPS/acoustic technique in Japan, comparing the situation in abroad. The topic extends not only to the scientific and technical issue but also to the administration and education for a sustainable system for a decadal plan. Fujimoto (2014) reviewed the history of seafloor geodetic surveys in Tohoku University and their contribution to understanding the subduction process. GPS/acoustic survey as well as seafloor extensometer and seafloor pressure measurements are addressed. Based on these results, contribution to reveal individual tectonic events and integrated interpretation are discussed. A paper by Fujimoto et al. (2014) was published in commemoration of being awarded the Tuboi Prize by the Geodetic Society of Japan, honoring their significant contribution in revealing the 2011 Tohoku-Oki Earthquake based on extensive and long-lasting surveys both onshore and offshore by stuffs in Tohoku University, and intensive interpretation based on their original data.

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8. Earth Tides and Ocean Tidal Loading

Ito and Simons (2011) used GNSS observations induced by ocean tidal loads to constrain density and elastic moduli for the crust and uppermost mantle below the western United States. They inferred that the asthenosphere has a low-density anomaly of ~50 kilograms per cubic meter. Ide and Tanaka (2014) first reported that tides could trigger tremors at the seasonal scale by focusing on long-term modulations of tidal amplitudes. They also estimated a multi-decadal variation in the tremor rate, which correlated well with the background seismicity during the period of 1965–2010 in the Nankai Trough. Kim et al. (2011) validated recent six ocean tide models (CSR4.0, GOT99.2b, NAO.99b, FES2004, TPXO7.1, and TPXO7.2) using superconducting gravity data recorded at Syowa Station by comparing with the observed loading effects.

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9. Application to Atmospheric, Ionospheric and Hydrological Researchers

Yoshida and Heki (2012) studied wet atmospheric delays measured by the Japanese dense GNSS array since 1990s, and revealed not only seasonal variations of precipitable water vapor but also their interannual changes possibly related to climate changes such as ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation). By comparing the atmospheric temperature profiles derived by GPS radio occultation observations before and after the 2010 eruption of the Eyjafjallajökull volcano, Iceland, and the 2011 eruption of the Puyehue volcano, Chile, Okazaki and Heki (2012) found localized and instantaneous cooling of the atmospheric near tropopause above the volcanoes.

Nakaegawa et al. (2012) investigated the dominant component of terrestrial water storage (TWS) and its contribution ratio at both seasonal and interannual time-scales. They also estimated mass changes due to mineral dust and sediment transports, and other crude oil, coal, and natural gas, iron, and bauxite mining. They examined the detectability of the mass changes by a satellite gravity mission. The result shows that it takes a long time for the mass changes to become equivalent to the interannual variability of TWS in magnitude in most regions or fields.

Sato et al. (2013) describes a system aimed at the near real-time monitoring of precipitable water vapor (PWV) by means of a dense network of Global Navigation Satellite System (GNSS) receivers. The PWV horizontal resolution is improved by using high-elevation satellites only such as the future Quasi-Zenith Satellite System (QZSS). Realini et al. (2014) proved that the GPS meteorology technique is useful to investigate severe weather conditions over Indonesia, complementing existing meteorological observation systems. The analysis of space-time variations of GPS-derived PWV has potential to allow the identification of precursors for nowcasting local convective rain.

Kinoshita et al. (2013) examined if numerical weather model (NWM) outputs really help to reduce the tropospheric effects in InSAR data, using three approaches. Their results indicate that the performance of the NWM outputs was depending on each case, and that they were not necessarily helpful in all the cases. Kinoshita et al. (2013) reported the first detection and analysis of a localized water vapor distribution obtained using interferometric synthetic aperture radar (InSAR) during the Seino heavy rain episode. The InSAR data retrieved during the ALOS/PALSAR emergency observations for the event revealed a radar line-of-sight (LOS) change of up to 130 mm within 10 km.

Cahyadi and Heki (2013) analyzed the total electron contents (TEC) before and after the 2007 Bengkulu earthquake, Indonesia, and found coseismic ionospheric disturbances (CID), atmospheric resonance with period ~4 minutes, and preseismic enhancement. Such signals, however, were not found for the 2005 Nias earthquake because of severe plasma bubble activities. After the 2011 Tohoku-Oki Earthquake (Mw 9.0), Heki (2011) found that the enhancement of ionospheric electrons started above the focal region ~40 minutes before the earthquake. He also showed that most earthquakes with M_w of 8.5 or larger are preceded by similar enhancements. In response to the paper criticizing Heki (2011), a rebuttal paper was published as Heki and Enomoto (2013). Another criticism for Heki and Enomoto (2013) was responded by Heki and Enomoto (2014). Ascending rockets cause ionospheric electron depletion due to chemical reaction between electrons and water vapor molecules in rocket exhausts. After the 2012 December missile launch from North Korea, Nakashima and Heki (2014) inferred its ascending track from its electron depletion signatures by analyzing the GLONASS (Russian GNSS) data.

Kobayashi et al. (2011) detected the spatial extent of liquefaction due to the 2011 Tohoku-Oki Earthquake by using changes of coherence values obtained from InSAR analysis secondarily. Ohtaki and Nawa (2013) reported analysis of the P-wave velocities in the sediment beneath the VERA Ishigakijima station and possible correlation between temporal variation of the P-wave velocity and rainfall (and/or soil moisture) at the station.

Harada et al. (2014) analyzed time series data of water level, and estimated natural periods (seiche) at Lake Ashinoko, Japan, and they revealed seismic seiche excited by the 2011 Tohoku-Oki Earthquake.

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10. Application to Glaciological and Cryospheric Science

During the last four years, the great details of cryosphere have been revealed by Synthetic Aperture Radar (SAR) analysis. Yasuda and Furuya (2013) examined the spatial-temporal changes in the surface velocities of the 36 major glaciers in West Kunlun Shan, northwestern Tibet, applying the offset-tracking technique to SAR data. Also, they first identified that four of them were surge-type glaciers. Using Envisat and ALOS SAR data, Muto and Furuya (2013) examined spatial-temporal changes in the surface velocities as well as the ice-front positions of major glaciers in south Patagonian Ice Field during 2002 to 2011. Using SAR images, Abe and Furuya (2014) examined spatial-temporal changes in the ice velocity of surge-type glaciers near the border of Alaska and Yukon, and found significant upstream accelerations from fall to winter, regardless of surging episodes. Moreover, whereas the summer speed-up was observed downstream, the winter speed-up propagated from upstream to downglacier. With InSAR analysis, Liu et al. (2012) detected the crustal displacements due to the unloading by the ice mass loss in Greenland, and showed how the data could constrain the quantity of ice loss.

Koike et al. (2012) analyzed time series of ERS-1/2 AMI intensity image within the period October 1991 to August 2000. The result revealed topographic changes such as movement of crevasse area as well as increase of the extent. Doi et al. (2011) used ASTER GDEM in differential interferometric SAR (DInSAR) analysis to remove topographic phase from a SAR intreferogram obtained from ALOS/PALSAR data. They also tried to detect ice sheet flow rate changes by taking difference between two DInSAR images.

Two GPS buoys consisted of a single frequency GPS receiver module and an Iridium satellite communication system were deployed on a floating ice tongue of Shirase Glacier, Antarctica for the first time. Aoyama et al. (2013) reported the derived flow rates at two site of the glacier.

Ozeki and Heki (2012) found that ionospheric (geometry-free) linear combination could be used to study multipath signatures caused by the interference between the direct and reflected microwave signals from GNSS satellites. They applied it to snow depth measurements at Shinshinotsu GNSS station in Hokkaido, Japan, and inferred its accuracy as ~6 cm by comparing with snow depth measurements from a local conventional meteorological station.

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11. Planetary Geodesy

Stokes' coefficients of global gravity fields are known to decay with the inverse of the square of degree. Hashimoto and Heki (2013) confirmed this Kaula's rule-of-thumb is valid for most terrestrial planets and the Moon, and found that their coefficients (Kaula constant) are inversely proportional to the square of the surface gravity.

Iwata et al. (2012) proposed to use four-way Doppler and inverse VLBI technique to measure rotational variation of Mars with a lander-orbiter configuration. The estimated accuracy of the rotation obtained by the inverse VLBI is better than 1 milli-arc-second including the systematic phase noise.

Goossens et al. (2011b) discussed orbit consistency using multiple types of tracking data from multiple SELENE spacecraft. The contribution of four-way Doppler, VLBI, and laser altimeter data to orbit precision are shown. Imamura et al. (2012) investigated electron density distribution in the vicinity of the lunar surface using SELENE radio occultation data. The results showed weak signatures of electron density enhancement with densities on the order of 100 cm^{-3} below 30 km altitude at solar zenith angles less than 60°. Ando et al. (2012) applied dual-spacecraft radio occultation technique to SELENE data to investigate the electron population in the vicinity of the lunar surface. The results suggested that any stable ionosphere with densities comparable to the ones observed by the Soviet Luna 19 and 22 missions does not exist. Sasaki et al. (2012a) summarized selenodetic observations of SELENE including four-way Doppler tracking, multi-frequency differential VLBI, and laser altimetry. Gravity signatures of far-side impact basins are mostly explained by topography except for the central high. Bouguer anomaly and crustal thickness variation of the Moon are shown. Araki et al. (2013) summarized a final report on laser ranging experiment by LALT on board SELENE (2007-2009); describing (1) General operational history, (2) Laser shot and data statistics, (3) Revisions to LALT topographic data, (4) Variations in laser output energy, and (5) Peak height analysis of laser echo pulses. Kamata et al. (2013) investigated the long-term evolution of basin structures using global lunar gravity field data obtained by SELENE tracking data and derived constraints for (1) the paleo-thermal state of impact basins and for (2) crustal column-averaged radioactive element concentrations for each of the three major lunar provinces.

Hanada et al. (2012) have developed a ground experiment model of the telescope for In-situ Lunar Orientation Measurement (ILOM) and made some experiments. Simulations with ray tracing method were also made and the effects of uniform temperature change upon the optical system were confirmed to be less than 1 milli-arc-second. Petrova et al. (2012a; 2012b) and Petrova and Hanada (2012; 2013) conducted computer simulations in order to estimate how accurately the lunar libration parameters are determined by ILOM. Stars to be observed by the polar telescope were selected at first, then modeling of observation equation and analysis of observed stellar tracks were made, and it was found that observations of polar stars are sensitive enough to distinguish between lunar models with different internal structure and properties.

Sasaki et al. (2012b) introduced selenodetic mission instruments proposed for SELENE-2 and future Japanese lunar missions, i.e., VLBI (inverse VLBI and differential VLBI) for gravity measurement to constrain tidal Love number, LLR (Lunar Laser Ranging) and ILOM (In-situ Lunar Orientation Measurement) for libration measurements. Kikuchi et al. (2014) described the differential VLBI mission proposed for SELENE-2. New operation modes are introduced for the purpose of electric power saving of the transmitter. S-band survival antenna which can be used at a temperature range between -200 and +120 degrees Celsius is designed.

Sasaki et al. (2012c) analyzed interior structure of small basins in and around South Pole-Aitken (SPA) Basin. Just around the rim of SPA, a distinct Moho uplift beneath Schrödinger corresponds to the presence of olivine and obscure circular structure Amundsen-Ganswindt has a significant Moho uplift, suggesting a buried impact structure.

Yamada et al. (2014) investigated how well the lunar interior structure can be determined using geodetic and seismic data based on the linear inverse method. They quantitatively showed that the accuracy of the core parameters will be improved by better determination of the Love number k_2 or h_2.

Harada et al. (2014) simulated the viscoelastic tidal response of a Moon which contains a low-viscosity layer at the core–mantle boundary. A layer with a viscosity of about 2×10^{16} Pa s is consistent with the geodetically observed frequency-dependent tidal dissipation at both monthly and annual periods.

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12. Regional Geodetic Activities

GSI has been assisting its regional geodesy projects on the creation of a geodetic reference frame and the prevention/mitigation of damages from natural disasters including large earthquakes through participation of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP), formerly known as the Permanent Committee on GIS Infrastructure for Asia and the Pacific (PCGIAP). GSI has been operating continuous GNSS observation in the Asia-Pacific region and analyzing the data combined with IGS data obtained in the region to establish regional reference frame consistent with ITRF (Suzuki and Miyahara, 2012). Suzuki and Miyahara (2013) constructed the analysis strategy to estimate enough stable coordinates. The data and results of analysis are also provided via the web and contributed to Asia-Pacific Regional Geodesy Project.

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13. Earth Rotation

Mass redistribution in large earthquakes may cause the shift of the Earth’s rotation pole. Kobayashi and Heki (2012) tried to detect such shifts by the 2004 Sumatra-Andaman, the 2010 Maule, and the 2011 Tohoku-Oki earthquakes by analyzing the time series of the positions of the excitation pole derived from space geodetic observations. Such shifts were, however, not significant under current measurement accuracies.

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