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Paper:

Detection of Seafloor Movement in Subduction Zones Around Japan Using a GNSS-A Seafloor Geodetic Observation System from 2013 to 2016

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In Japan, interplate megathrust earthquakes frequently occur in subduction zones where oceanic plates subduct beneath continental plates, and it is important to elucidate the physical mechanism involved in such earthquakes to prevent associated disasters. Crustal movement data provide essential information to understand plate motion and earthquake source processes. We developed a system that combines GNSS measurements and acoustic ranging techniques to detect seafloor crustal movement. This paper reports the acquisition of recent seafloor crustal movements obtained during campaign observations with a survey vessel, from 2013 to 2016.

Keywords: GNSS-A, seafloor geodesy, crustal deformation, subduction zone

1. Introduction

The Pacific and Philippine Sea plates subduct beneath continental plates along the Japan Trench and Nankai Trough, respectively, on which the Japanese archipelago rests, at the rate of several centimeters a year, resulting in repeated subduction-zone megathrust earthquakes. Japan has experienced frequent damage related to this type of earthquake, which are caused by accumulated strain as the continental plate is deformed by oceanic subduction.

It is important to elucidate the physical process of earthquakes to enable associated disaster prevention in Japan. Observations of crustal movement are useful for estimating the amount of plate deformation and strain accumulated. Satellite GNSS radio waves are being used today for high-accuracy positioning on land allowing the monitoring of daily crustal movements to within 1 cm. However, most focal regions of actual megathrust earthquakes are located underneath the seafloor at considerable distances from the coast, and it is thus difficult to estimate the condition of these focal regions with an adequate accuracy using only crustal movement data observed on land. It is therefore essential to obtain crustal movement data for the seafloor at positions closer to these focal regions, to elucidate the mechanisms involved in the occurrence of interplate megathrust earthquakes along trenches.

The Japan Coast Guard has been developing technology for precise seafloor geodetic observation using a combination of GNSS and acoustics ranging since late 1990s and began actual observations at Kumano basin in 2000 [1]. In addition, the importance of seafloor geodetc observations was promulgated in policy guidelines established by the governmental Headquarters of Earthquake Research Promotion, which promotes earthquake surveys and observations in Japan. The associated Earthquake Survey and Observation Plan stipulated that the Japan Coast Guard should "set up seafloor observation sites at intervals of 100 km on the landward side along trenches." Following implementation of the plan, the Japan Coast Guard established an observation network on the landside slopes along the Japan Trench and the Nankai Trough and is currently conducting observations repeatedly at 23 observation sites. There are approximately 60 observation sites in existence that have been established by Japanese research bodies (including universities), which represent a seafloor geodetic observation network with a density unparalleled anywhere else in the world (**Fig. 1**).

This paper reports seafloor crustal movement velocities obtained from steady observations conducted by the Japan Coast Guard from 2013 to 2016.

2. GNSS-Acoustic Ranging Combination Technique

2.1. Overview

Radio waves are considerably attenuated in seawater, and it is not possible to determine the accurate position of deep seafloors using radio waves, although this can be achieved with GNSS on land. In the 1980s, Spiess et al. (from the Scripps Institution of Oceanography) [2] proposed GNSS-acoustic ranging (GNSS-A) to overcome this issue. This technology enables seafloor geodetic observations by combining the use of GNSS positioning on the sea surface and acoustic ranging in the sea. Research and development to realize seafloor geodetic observations has since been conducted in the United States and Japan, and now approximately 60 observation points have

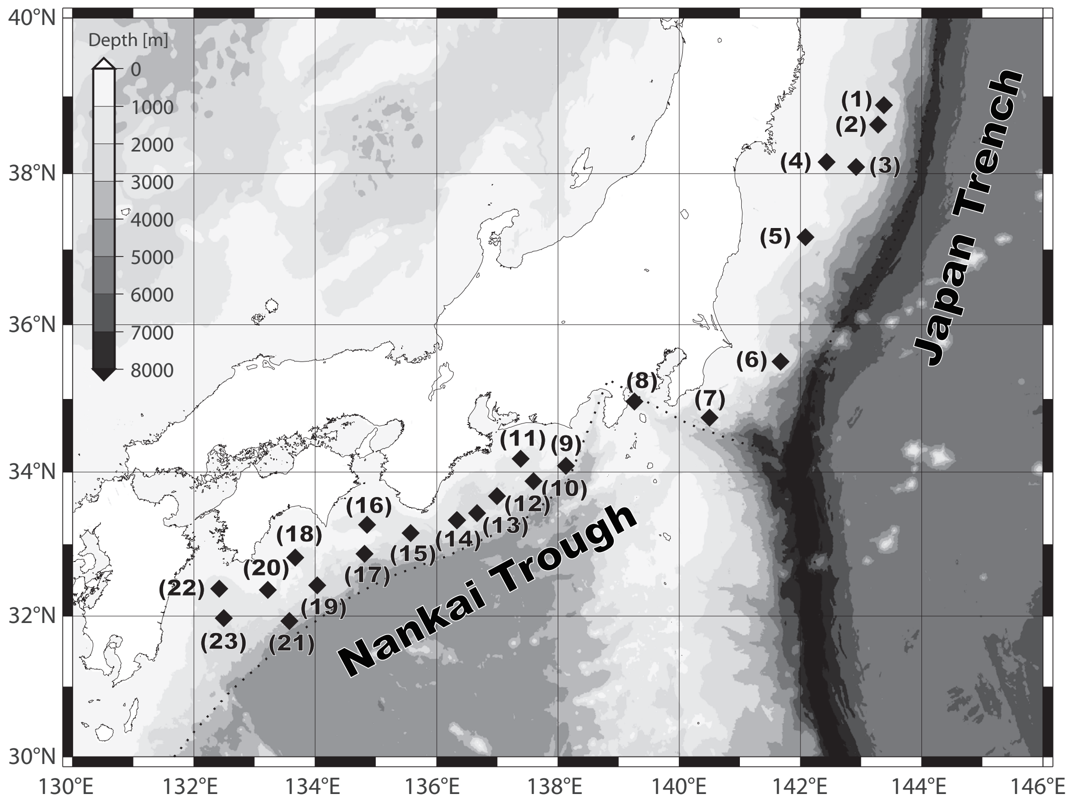

Fig. 1. Locations of seafloor GNSS-A sites (diamonds) shown on topographic map around Japan. Site names are listed in **Table 1**.

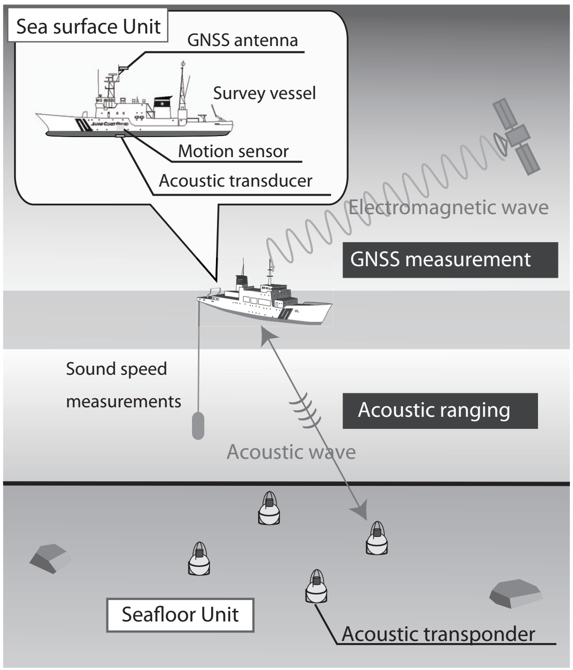

Fig. 2. Schematic figure of GNSS-A seafloor geodetic observation system.

been established around Japan. This section provides an overview of the GNSS-A observation system operated by the Japan Coast Guard [3].

GNSS-A based seafloor geodetic observations involve the use of two systems: seafloor unit established on the seafloor and a sea surface unit, which is a survey vessel equipped with observation instruments (**Fig. 2**). The seafloor unit are used as benchmarks, and observations are made on the sea surface unit to measure the positions with a centimeter-level accuracy. This positioning is conducted repeatedly to detect positional changes of seafloor unit and to determine seafloor crustal movements. The sea surface unit has an GNSS antenna that measures the position of the survey vessel moving on the sea surface, an acoustic transducer that measures the range to the seafloor unit, and a motion sensor that correlates the position of the two equipment. The position of the sea surface unit is determined with high accuracy using kinematic GNSS positioning. The seafloor unit consists of multiple acoustic transponders (usually four) set on the deep seafloor at depths of about one to three thousands of meters. The acoustic transponders receive acoustic signals transmitted by the sea surface unit and return the signals. The distance between the sea surface and seafloor unit is determined by measuring the round-trip travel time of the acoustic signals. The absolute position of the seafloor unit on the deep seafloor is determined using a combination of the distance between the sea surface and the seafloor unit, which is obtained by acoustic ranging, and the position of the sea surface unit, which is obtained by GNSS positioning.

2.2. GNSS Measurment

The position of the sea surface unit is determined using kinematic GNSS positioning. This is achieved by conducting simultaneous observations at a GNSS station on land, which provides a positioning reference, and at the sea surface unit (survey vessel) and then post-analyzing data obtained to determine the time-varying position of the sea surface unit relative to the land station at a centimeter-level.

The major error factor in GNSS positioning is the velocity variation in radio waves due to effects in the troposphere and ionosphere that provide the propagation paths for the radio waves. However, as the error factors common to the two observation points are cancelled out via baseline analysis when measuring the position relative to the reference station, it is possible to measure the position with a high accuracy. This technique is therefore widely used in surveying and research. Highly accurate results are obtained when the baseline distance between the reference and moving stations is a distance of 10 km or less, as the propagation paths of the radio waves from the GNSS satellite to the two stations are close, and the effects of errors are sufficiently cancelled out by applying the data differential. However, when there is a long baseline distance, the effects of the troposphere and ionosphere are not sufficiently cancelled out as the propagation paths are distant from each other. As there is a considerable baseline distance between the sea surface unit and land stations (often exceeding 100 km), the accuracy of baseline analysis is therefore not as good as it is on land.

To obtain stable results for sea surface unit, analysis was conducted using interferometric translocation (IT) [4], which is a software program developed for kinematic GNSS positioning using long baseline distances. This program incorporates technology aimed at removing error factors that appear with long distances, including correction and estimation of the delay time in the ionosphere and troposphere, to improve the accuracy of positioning using long baseline distances.

2.3. Acoustic Ranging

Acoustic ranging is a measurement system using the distance between acoustic signals from a point on the sea surface and the seafloor unit. Acoustic signals are transmitted by an acoustic transducer mounted on the hull of the survey vessel (the sea surface unit) and received by the acoustic transponder (the seafloor unit). After a given time interval, the acoustic transponder transmits an acoustic signal back to the sea surface unit; when this signal is received by the sea surface unit, the round-trip travel time of the acoustic signal is measured.

Acoustic signals travel in seawater at a speed of approximately 1,500 m/s, and the round-trip travel time must be measured with an accuracy of several micro-seconds or less to enable positioning with a centimeter-level accuracy. As signal intensity is attenuated, and the waveform is distorted by traveling to and returning from the deep seafloor at a depth of several thousands of meters, wave correlation medhod can be used to obtain accurate time measurements. The acoustic signals used for observations is a 10 kHz pulse waves coded by M-sequence, which is a pseudorandom binary sequence. The advantage of using signals coded by a pseudorandom M-sequence is that it is possible to recreate the original signal by correlation processing with a theoretical waveform, even when the signals are buried in noise and have become weak, or when the waveforms are distorted. This processing makes it possible to detect the arrival time of acoustic signals with high accuracy.

However, to convert the round-trip travel time of acoustic signals (which are the measurement values obtained by acoustic ranging) into distance, it is necessary to know the acoustic wave velocity in the seawater. This requires suitable measurements of temperature and the conductivity of seawater at depth-increments of 1 m, which are obtained in parallel with acoustic ranging. The speed of the acoustic waves is then determined using the measured water temperature and conductivity.

2.4. Seafloor Positioning

The position of the seafloor unit is determined using a combination of the position of the sea surface unit, which is obtained by kinematic GNSS positioning, and the distance (round-trip travel time) between the sea surface and seafloor unit obtained from acoustic ranging. The basic principle is based on a “three-dimensional compass,” where multiple spherical surfaces are obtained using multiple observation reference point positions and the ranges between these points, and intersections are found between these surfaces.

In this respect, it is necessary to link two positioning points installed on the sea surface unit, i.e., the positions of the GNSS antenna and the acoustic transducer. The relative positions of these two devices are measured on the survey vessel. The sea surface unit is equipped with a motion sensor, which simultaneously records the time-varying angles (pitch, roll) and azimuth of the vessel. The position of the acoustic transducer is determined from the position of the GNSS antenna (obtained by kinematic GNSS), the relative positions of the two devices, and the three-axis rotating angles (which are measured using the motion sensor). The time used by the observation instruments is synchronized using a rubidium atomic clock, so that the time lag that occurs when combining the two different positioning data of GNSS positioning and acoustic ranging is maintained within a negligible level.

In analysis, the position of the seafloor unit is determined using the least squares method, to minimize the difference between the theoretical round-trip travel time of the acoustic wave and the actual measured travel time. The effect of random errors is minimized, as the positioning accuracy is improved by increasing the number of acoustic ranging data . In practical, it is necessary to obtain approximately 1000 acoustic ranging measurements for a single acoustic transponder to secure desired accuracy; this requires an observation time of approximately one day at each observation site.

3. Result and Discussion

The crustal movement velocity is determined from the trend of the regression line relating to the time-series positions of the seafloor unit obtained from observations. The uncertainty of the trend must be maintained within approximately 1 cm/yr (95% CL) to detect minute crustal movements of several centimeters per year.

It is necessary to improve the positioning accuracy and increase the number of observations to reduce the uncertainty of regression line trend. The accuracy relating to repeated positioning of observations can be obtained in terms of residuals from the regression line, which generally displays standard deviations of approximately 2–3 cm. Nevertheless, deviations in excess of 10 cm can occur due to the effects of systematic errors caused by the ocean environment, particularly in relation to water temperature disturbances. To enable observations, the survey vessel needs to visit the observation site to acquire data; therefore, the observation frequency per observation site is limited to two or three times annually. With the current positioning accuracy and observation frequency it is necessary to accumulate data over a three or four-year period to ensure the uncertainty of the regression line trend is within about 1 cm/yr.

Therefore, although it is possible to grasp the average velocity over three to four years with an uncertainty of 1 cm/yr using the current observation technique, it is not possible to achieve accuracies that allow the assessment of seasonal movements or very small short-term movements (such as slow slip events and other aseismic slips) that can be detected using terrestrial GNSS.

Figure 3 shows the crustal movement velocity obtained by regression analysis of time-series positions of seafloor units obtained from observations conducted over four years from 2013 to 2016. The time-series data used can be viewed on the website of the Japan Coast Guard [5]. The stable part of the Eurasian plate, obtained from the Nuvel-1A model, is used as the reference for the velocity. The results of terrestrial GNSS are based on the F3 solution of the GNSS Earth Observation Network System (GEONET) of the Geospatial Information Authority of Japan. The period and number of observations of data used for analysis, standard deviations and correlation coefficients of regression analysis results are presented in **Table 1**.

3.1. Japan Trench

The post-seismic deformation of the 2011 Tohoku-oki earthquake continue on land in northeast Japan and on the seafloor. Aseismic fault slips, which are known as afterslips, occur after megathrust earthquakes. Afterslip for this earthquake should occur in an eastward direction toward the Japan Trench; however, the velocity of the seafloor off the coasts of Miyagi and Iwate prefectures points to the west, which is in direct opposition to the direction of terrestrial displacements. Terrestrial GNSS displacement results revealing eastward displacements can mostly be attributed to afterslip but the westward seafloor displacements cannot be explained in this way.

This strongly suggests that underground mantle movements have an important effect on surface ground movements. The mantle, which is softer than the crust on the surface, has a viscoelastic property and displays fluid-like properties over long time-scales. When massive faulting occurs during an earthquake, viscous flow can occur in the mantle within the vicinity : this type of movement is called viscoelastic relaxation ([6] for example). Although it has been known that such processes occur underground after megathrust earthquakes, this is the first time that pronounced reverse movements have been observed both on land and at sea.

Watanabe et al. [7] reported results of GNSS-A observations up to January 2014, and various research groups have constructed models of viscoelastic relaxation based on these results (for example [8–12]). However, the results presented in this current paper are based on new observations that were made subsequent to those of Watanabe et al. [7]. Since the effects of afterslip and viscoelastic relaxation decrease with the time, it is expected that the crustal movement pattern will also undergo gradual changes. Therefore, these latest results can now be used in updated model studies. The shift in crustal movement occurring after a megathrust earthquake provides important information for assessing changes in seismic activities within the area and the re-accumulation of strain. It is thus important that observations continue and that basic information is collected to enable disaster prevention plans to be developed in northeastern Japan.

3.2. Nankai Trough

Deformation occurs in southwestern Japan from subduction of the Philippine Sea plate in the Nankai Trough, which shows that strain is accumulating prior to the next megathrust earthquake. Deformation of the landward plate depends on the condition of coupling at the plate boundary: the stronger the coupling, the greater the deformation. It is thus possible to estimate the coupling status of underground plates from crustal movements on the surface. However, as the focal regions of megathrust earthquakes are located beneath the seafloor at considerable distances from the coast, estimations based on the results of terrestrial GNSS observation provide limited accuracy. However, the results of seafloor GNSS-A provide important data; Yokota et al. [13] used results of GNSS-A observations from 2006 to May 2015 to estimate the slip deficit rate at the plate boundary and show that coupling in the area is distributed in a spatially heterogeneous structure. While results from this current observation do not depart greatly from those of Yokota et al., it is known that coupling at a plate boundary may not remain stable and may instead undergo variations over time. It is thus necessary to monitor such variations to gain an understanding of the preparatory processes for the next megathrust earthquake, and observations should be continued to enable the collection of basic information that could be used

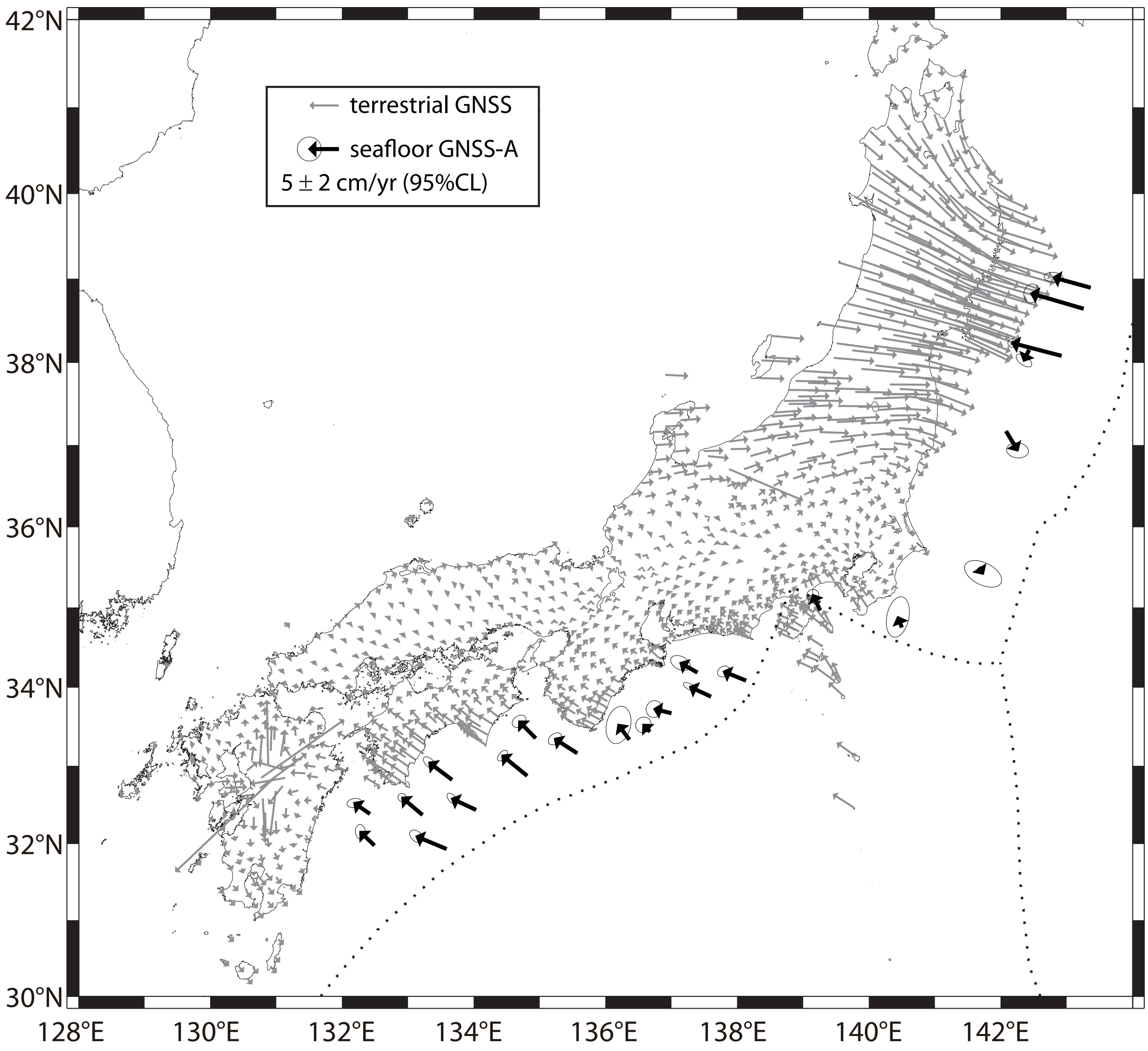

Fig. 3. Crustal movement velocities at seafloor GNSS-A sites and terrestrial GNSS sites relative to stable part of Eurasian plate. Seafloor velocity vectors and associated 95% confidence intervals are shown using black arrows and ellipses, respectively. Terrestrial velocity vectors were calculated for the period from Apr. 1, 2013 to Apr. 1, 2017 using GEONET stations and are shown using light grey arrows. Observation period of GNSS-A seafloor sites is presented in **Table 1**.

to minimize the effect of disasters in the event of a Nankai Trough earthquake.

4. Summary and Outlook

GNSS-A enables seafloor geodetic observations, and its use has enabled underground conditions in the focal regions to be monitored with a greater accuracy than was previously possible using terrestrial GNSS observations alone.

Results of observations can be used to further understand mechanisms involved in subduction-zone megathrust earthquakes, enable improved predictions of intense ground motions and tsunamis, and to ultimately design countermeasures that can be employed in the event of future earthquakes. For example, the plate boundary conditions obtained from the present observations can be incorporated to produce simulations of earthquake and tsunami scenarios [14] that better reflect actual conditions.

However, the positioning accuracy and numbers of observations with GNSS-A are low compared to terrestrial GNSS, which has been successfully used to detect minute short-term deformation phenomena (such as slow slip) and has enabled studies to examine the relation between such aseismic slip and megathrust earthquakes [15, 16]. Although such phenomena are also thought to occur on the seafloor, it is extremely difficult to detect them with the present performance level of GNSS-A. If monitoring of short-term phenomena such as slow slip on the seafloor was possible, this would further our understanding of megathrust earthquakes. Therefore, research and development efforts should continue with the aim of improving the positioning accuracy and number of GNSS-

Table 1. Seafloor GNSS-A site velocity in Eurasia-fixed reference frame and associated 1 σ uncertainties.

	Position		Velocity [cm/yr]		SD [cm/yr]		Corr.		
Site name	Lat. (°E)	Long. (°N)	V_e	V_n	σ_{V_e}	σ_{V_n}	ρ	Period	Number of observation
(1) KAMN	38.89	143.36	−6.2	1.7	0.5	0.3	−0.1	Jun. 2013 - Oct. 2016	12
(2) KAMS	38.64	143.26	−8.8	2.6	0.4	0.5	0.1	Jan. 2013 - Oct. 2016	13
(3) MYGI	38.08	142.92	−8.3	2.2	0.3	0.3	0.1	Jan. 2013 - Oct. 2016	15
(4) MYGW	38.15	142.43	−0.9	−1.8	0.4	0.4	−0.5	Jul. 2013 - Oct. 2016	14
(5) FUKU	37.17	142.08	1.9	−3.3	0.6	0.4	−0.1	Jul. 2013 - Oct. 2016	12
(6) CHOS	35.50	141.67	0.7	−1.1	0.9	0.6	−0.4	Jul. 2013 - Oct. 2016	8
(7) BOSN	34.75	140.50	−0.7	1.8	0.6	1.0	0.3	Jul. 2013 - Oct. 2016	9
(8) SAGA	34.96	139.26	−1.2	2.6	0.3	0.3	0.0	Jul. 2013 - Oct. 2016	17
(9) TOK1	34.08	138.13	−3.8	1.5	0.4	0.3	0.2	Jan. 2013 - Nov. 2016	16
(10) TOK2	33.88	137.60	−3.6	1.7	0.4	0.2	−0.6	May 2013 - Oct. 2016	13
(11) TOK3	34.18	137.39	−2.9	1.6	0.5	0.4	−0.4	Jan. 2013 - Oct. 2016	11
(12) KUM1	33.67	137.00	−2.9	0.7	0.4	0.5	0.1	May 2013 - Oct. 2016	10
(13) KUM2	33.43	136.67	−1.1	1.2	0.4	0.4	0.1	Jan. 2013 - Oct. 2016	12
(14) KUM3	33.33	136.36	−1.8	2.5	0.7	1.0	0.2	Jun. 2013 - Nov. 2016	11
(15) SIOW	33.16	135.57	−3.8	2.4	0.4	0.3	0.4	Jan. 2013 - Nov. 2016	11
(16) MRT1	33.35	134.94	−2.8	2.9	0.4	0.3	0.3	Jun. 2013 - Nov. 2016	11
(17) MRT2	32.87	134.81	−4.2	3.4	0.3	0.3	0.5	Jan. 2013 - Nov. 2016	16
(18) TOS1	32.82	133.67	−3.9	2.9	0.3	0.3	−0.5	Jan. 2013 - Nov. 2016	13
(19) TOS2	32.43	134.03	−4.1	1.9	0.3	0.3	−0.6	Jan. 2013 - Nov. 2016	15
(20) ASZ1	32.37	133.22	−3.4	2.9	0.3	0.2	−0.1	Jan. 2013 - Nov. 2016	15
(21) ASZ2	31.93	133.58	−5.0	2.1	0.4	0.4	−0.4	Jan. 2013 - Nov. 2016	15
(22) HYG1	32.38	132.42	−2.6	1.8	0.4	0.3	0.1	Jan. 2013 - Nov. 2016	16
(23) HYG2	31.97	132.49	−2.3	2.3	0.3	0.4	−0.1	Jan. 2013 - Nov. 2016	16

A observations used, and study groups such as the Japan Coast Guard and universities are currently engaged in research in this respect.

The most major error factor in GNSS-A observation lies in variations in acoustic wave speeds in the seawater. Since the residual of observation data obtained by acoustic ranging includes information about error factors, methods used to extract error information are important for improving accuracy. The approach of such methods is similar to that used to estimate the delay time of radio waves due to water vapor in GNSS observations. While it is possible to improve GNSS accuracy by using information from multiple propagation routes (as radio waves simultaneously transmitted from several satellites are used), only a single propagation path exists in GNSS-A and measurements are obtained using observations from a survey vessel. Although the use of multiple sea surface stations would be a valid way of resolving this problem, this has not yet been possible because of the increased operational complexity and costs involved, and current research thus continues to focus on the software approach, such as improving analytical methods.

Continuous observation is possible with GNSS, which employs an online unmanned observation system; however, this is not possible with GNSS-A, as a survey vessel must be dispatched to the observation site. It is thus necessary to develop a ocean unmanned observation system to realize continuous observation, as has been developed for land areas. Mooring buoys or unmanned surface vehicles (USVs) could be used as unmanned sea surface units to replace survey vessels; and research and development efforts are underway in this respect to realize future continuous observation.

The limited number of observation sites is another issue that needs resolving. The current observation network is limited to sea areas extending from the Japan trench to the Nankai Trough, while the Kuril Trench or Ryukyu Trench are blank zones. In addition, the density of observation sites in the Japan Trench and Nankai Trough are low compared to the terrestrial GNSS observation network, and coupling at plate boundaries has not been estimated in detail. Although construction of a seafloor observation network involves considerable costs compared to a terrestrial network, it is thus necessary for research group of relevant bodies to coordinate efforts to strategically strengthen the observation network.

Methods other than GNSS-A observation have been developed in recent years to observe seafloor crustal deformation. For example, water-pressure gauges connected to a submarine cable-type earthquake/tsunami observation network (for example [17]) could be used to detect vertical crustal displacements. Slow-slip events have been successfully detected using observations of pore-water pressure in boreholes connected to submarine cables [18]. Therefore, it is necessary to combine GNSS-A observations with other observation methods to compensate for the shortage of seafloor observation points and enable the comprehensive assessment of crustal activities.

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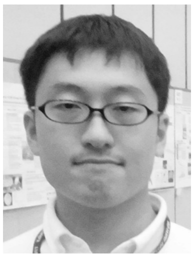

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