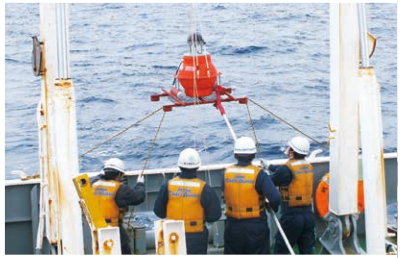
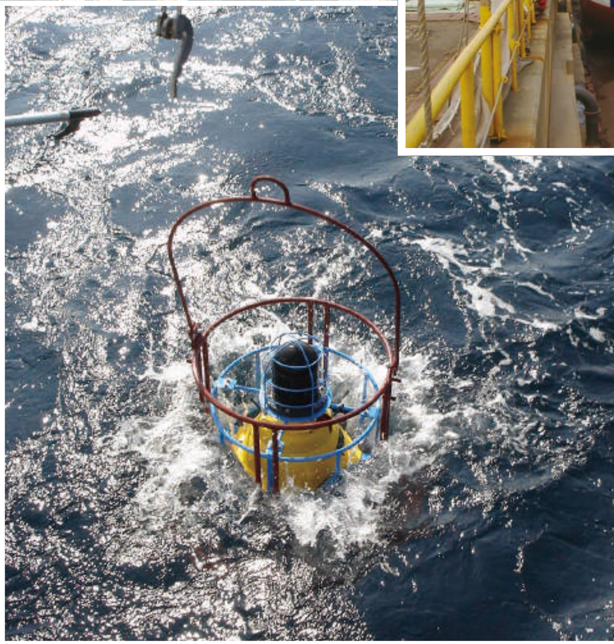
Seafloor geodetic observation

GNSS-A system





Geodesy & Geophysics Office, Hydrographic Surveys Division,
Hydrographic & Oceanographic Department, Japan Coast Guard

Collaborated with Yokota lab. Institute of Industrial Science, U. Tokyo

JHOD web site

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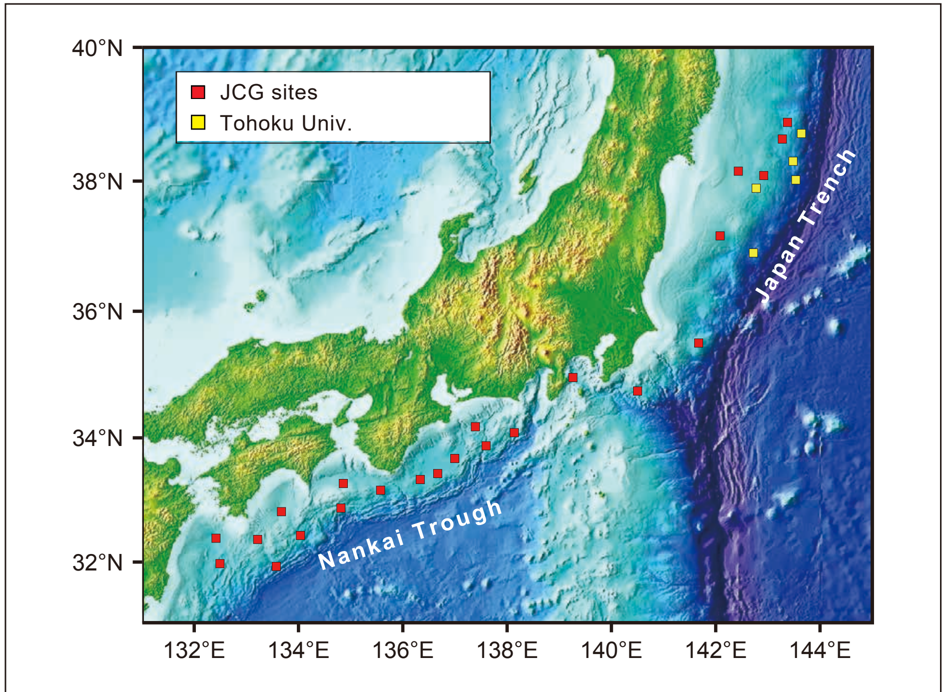
Outline
of seafloor geodetic observation

The Japan Coast Guard carries out seafloor geodetic observation using the "GNSS-Acoustic ranging combination system (GNSS-A)" and measures the seafloor movement around Japan. This observation contributes to earthquake disaster prevention by providing valuable data for elucidating the mechanism of huge earthquakes that occur along the Japan Trench and the Nankai Trough.

1 Seafloor geodetic observation

Observation networks have been deployed in the focal regions of the 2011 Tohoku Earthquake and the Nankai Trough Earthquake which is expected to occur in the future. Seafloor geodetic observation is conducted regularly in these regions.



JCG seafloor geodetic observation network (June 2018)

Geodetic observation

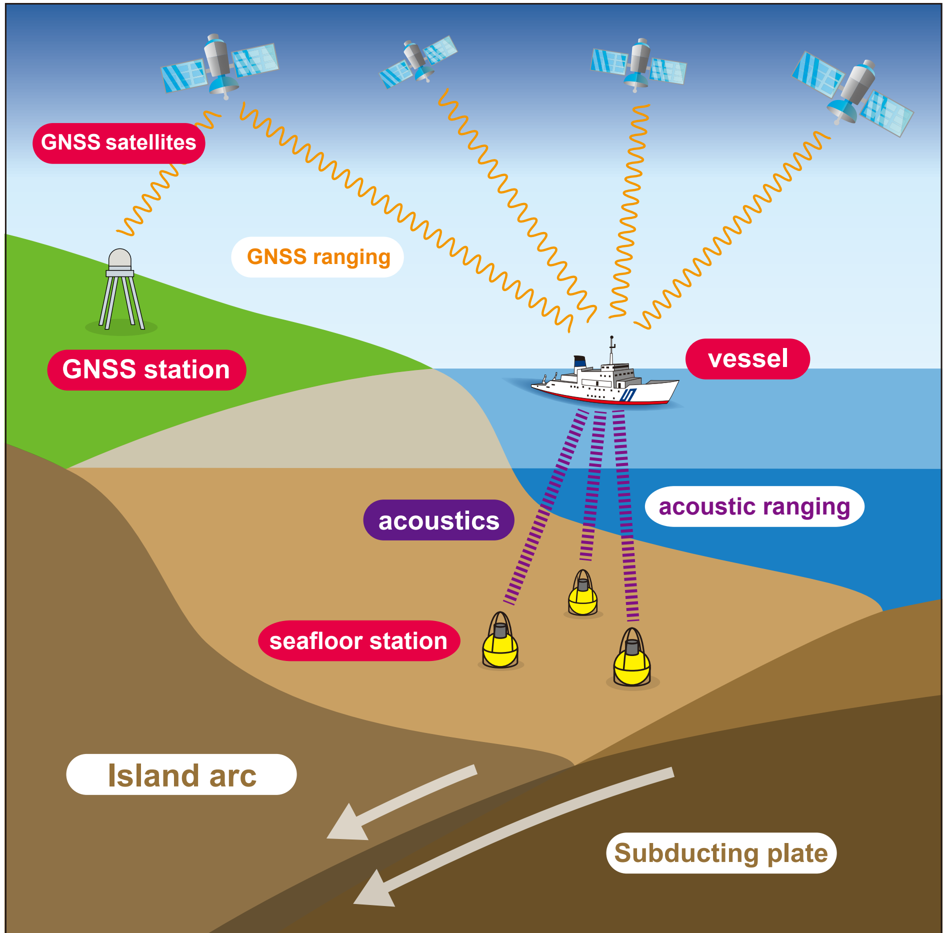
Geodetic observation is performed to understand the phenomenon that occurs under the ground. The phenomena that occur in relatively shallow places in the Earth have some effect on the Earth's surface, such as magma movement under the ground which causes the ground to expand, and earthquakes which move the surface. We observe such ground movement by geodetic observations.

2 GNSS-Acoustic combination technique

With the spread of GNSS, it has become possible to measure the movement of the ground with a precision of 1 cm or less on land. However, GNSS cannot directly measure the seafloor movement since radio waves are unable to reach the seafloor.
Employing the know-how of seafloor survey and crustal movement observation that have been cultivated through the production of nautical charts, Japan Coast Guard has done research and development to measure seafloor crustal movement in collaboration with the Institute of Industrial Science, University of Tokyo by combining the radio wave and acoustic techniques

❶ using GNSS, determine the survey vessel position（GNSS ranging）
❷ using acoustics, measure the range between the vessel and seafloor station

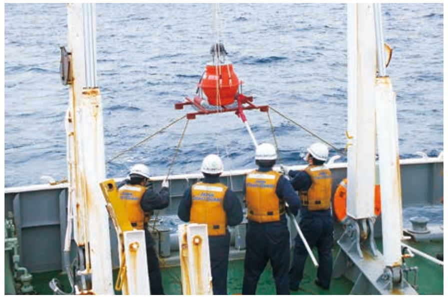
An observation system (GNSS-A) that precisely measures a position on the seafloor was put to practical use.



Outline of GNSS-A system

Purpose
of seafloor geodetic observation

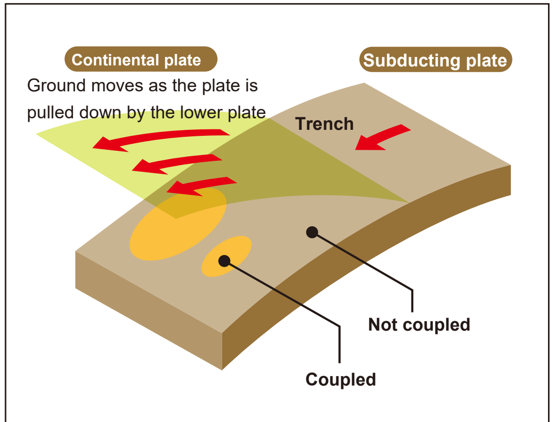
The Japan Coast Guard carries out seafloor geodetic observations at the floor of the continental plate along the Japan Trench and the Nankai Trough.
The main objectives of these observations are to estimate the interplate coupling and the slip distribution during earthquakes, and to provide these data for elucidation of the mechanism of earthquakes.



1 Understanding the interplate coupling conditions

Megathrust earthquakes occur repeatedly at certain places. This is due to the unevenness of interplate coupling at the interface of the continental plate and the subducting oceanic plate.

At regions where the plates are coupled strongly, the subducting oceanic plate pulls the continental plate, causing strain to accumulate in the continental plate. A huge megathrust earthquake occurs when the accumulated strain is released suddenly. On the other hand, the oceanic plate subducts smoothly along regions where the interplate coupling is weak. It is hypothesized that the accumulation of the strain in the continental plate is smaller in regions where the interplate coupling is weak. By accurately determining the distribution of the strength of interplate coupling, we can deepen our understanding of megathrust earthquakes, and promote disaster prevention that are more effective against earthquakes that are expected to occur in the future.

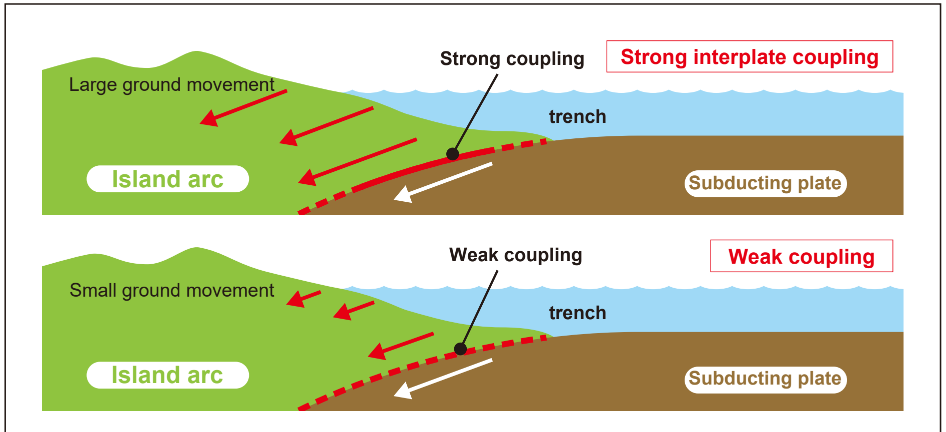


Interplate coupling

Tectonic plates
Tectonic plates are hard pieces of crust covering the Earth surface. Earthquakes occur frequently at boundaries where the plates collide. Mechanism of earthquakes and the formation of mountains and continents can be revealed through the observation of the crustal surface movement.

Megathrust earthquake
Megathrust earthquake occurs at a converging plate boundary such as an oceanic trench. Many of the huge earthquakes exceeding magnitude 8 are known to be this type. Megathrust earthquakes tend to have larger focal regions and magnitudes than inland earthquakes.

Geodetic observation is one of the powerful tools to estimate the distribution of interplate coupling. A movement that occurs underground affects the surface; simply, the movement of the surface is large if the continental plate is pulled strongly, and small if the pull is weak. By measuring the movement of the surface, the movement underground can be estimated. In Japan, geodetic observations carried out by the Geospatial Information Authority of Japan (GSI) using an extensive GNSS network on land are achieving results. However, most of the focal regions of megathrust earthquakes are offshore, making it necessary to observe not only the crustal movement on land but also on seafloor to accurately estimate the distribution of interplate coupling.



Interplate coupling conditions and surface movement

GNSS
GNSS (Global Navigation Satellite System) is a generic term that refers to a satellite system that precisely measures the position on the Earth by radio wave communication. There are several systems, each operated by different countries, such as the GPS (Global Positioning System, USA), GLONASS (GLObal'naya NAvigationnaya Sputnikovaya Sistema, Russia), and the QZSS (Quasi-Zenith Satellite System, Japan).

2 Submission of observation results

The results obtained from seafloor geodetic observation are regularly submitted to governmental committees related to earthquake disaster prevention. Together with the results obtained by other organizations, these results are important data for conducting comprehensive assessment of earthquakes and disaster prevention.

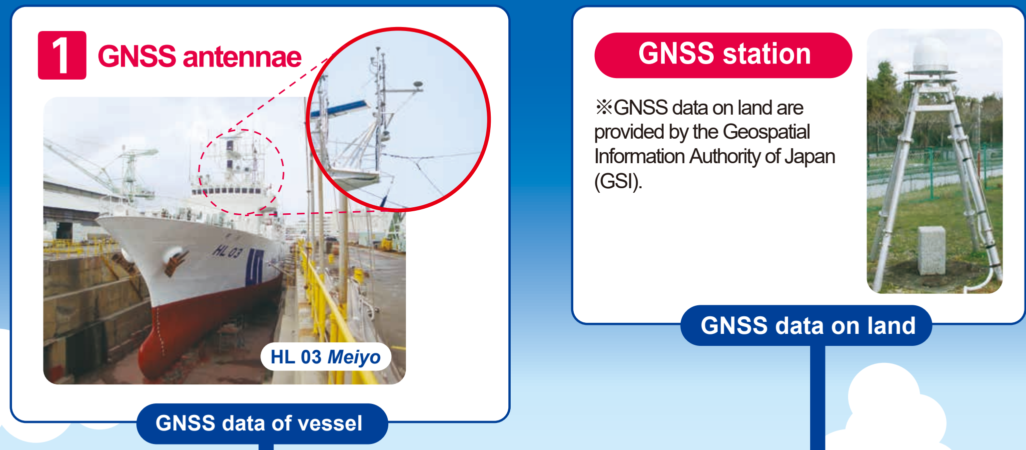
Earthquake Research Committee
A committee under the Headquarters for Earthquake Research Promotion that collects, organizes, and analyzes results of observation, survey, and research related to earthquakes that are achieved by relevant administrative organizations and universities. Comprehensive evaluation is done according to these results.

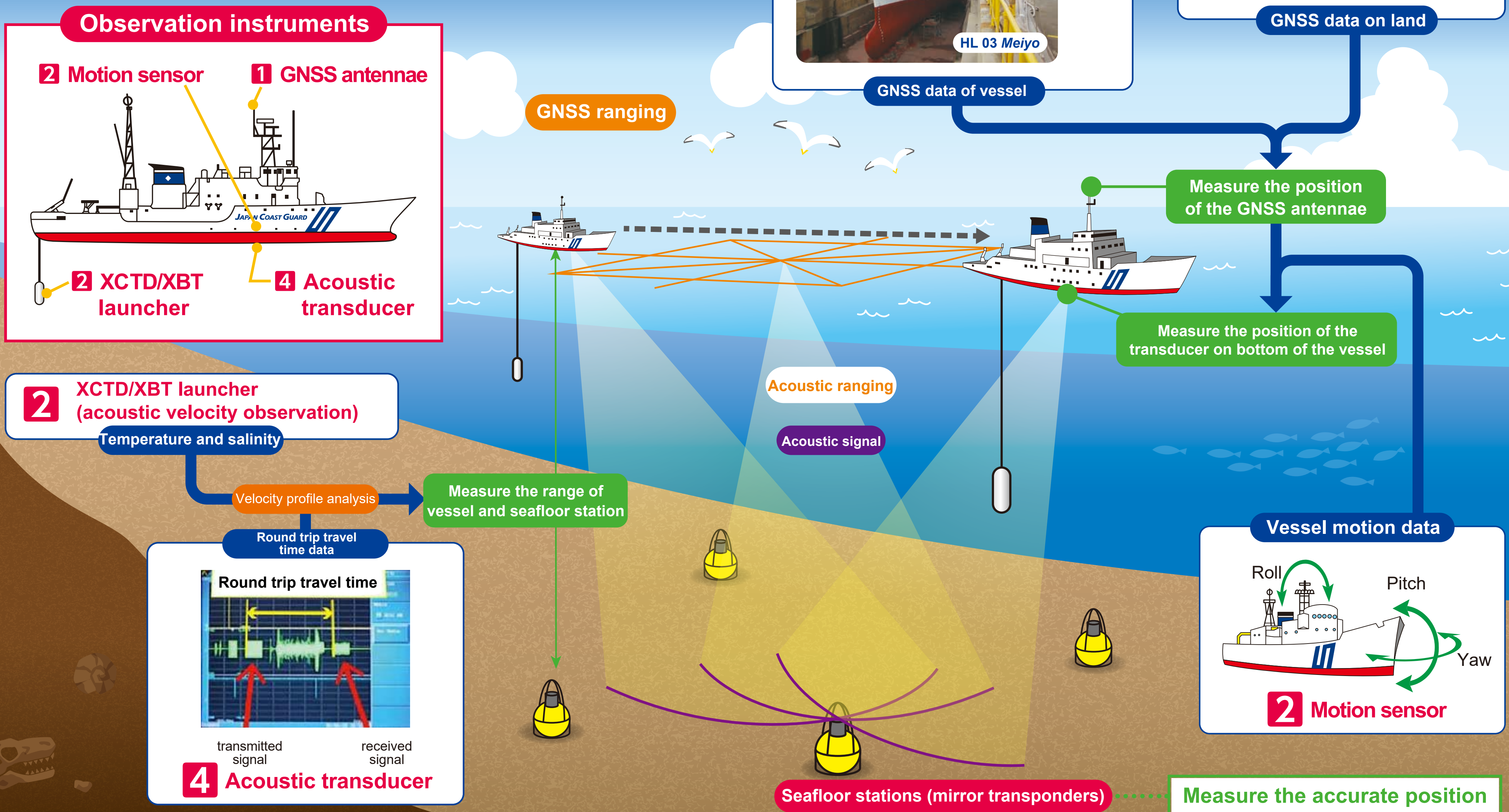
Coordinating Committee for Earthquake Prediction
A committee that exchanges information of surveys, observations, and research results on earthquake prediction, and conducts academic studies based on these information.

Advisory Council for Evaluation of Earthquakes along the Nankai Trough
A council held every month by the Japan Meteorological Agency that evaluates the possibility of earthquakes across the Nankai Trough region, in conjunction with the Prediction Council for the Area under Intensified Measures against Earthquake Disaster for the Tokai region.

Outline of GNSS-A system

In the GNSS-A system, a variety of instruments are used to accurately measure the position of the seafloor station (mirror transponder).





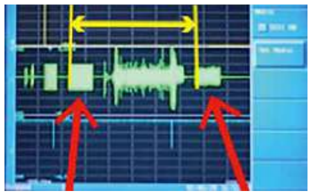
Details of GNSS-A system

1 Acoustic ranging


Crew working on acoustic ranging

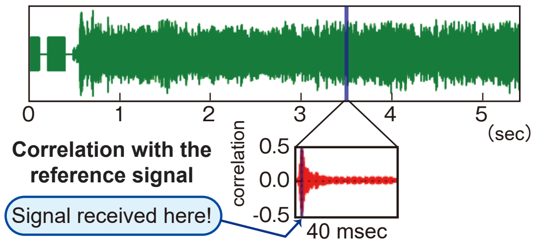
Since radio waves cannot travel far distances underwater, acoustic waves are used to measure the range between the survey vessel and the seafloor station (acoustic ranging). The seafloor station is an acoustic instrument called the mirror transponder, which receives the signal transmitted by the transducer (an instrument that communicates acoustic signals) installed on bottom of the vessel. The seafloor station sends the received signal back to the vessel's transducer, and the round-trip travel time of the signal is measured.


Transducer on bottom of the vessel


Transmitted signal　Received signal

Observed acoustic signal
(Range measured from round trip travel time)

Received signal pattern



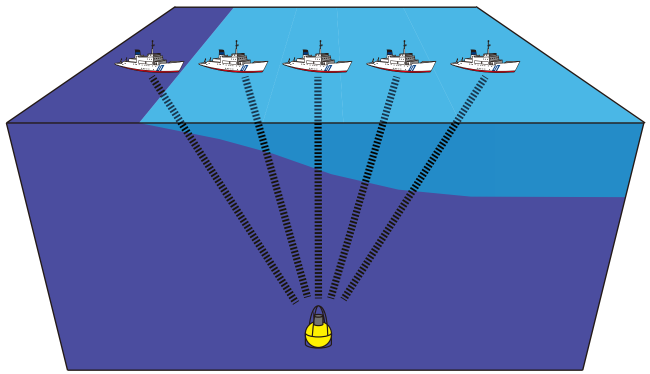
As a result of traveling back and forth few thousand meters of depth, the intensity of the signal diminishes and the signal pattern is deformed. In order to measure the round-trip travel time in precision of few microseconds, the wave shape correlation analysis is employed. By using this method, fine signals that are hidden in noisy signals can be identified.

Correlation analysis of the received signal

2 Acoustic velocity measurement

In order to calculate the range between the vessel and the seafloor station from the measured round-trip travel time, the acoustic velocity profile must be determined accurately. Since acoustic velocity varies significantly by water temperature and salinity, measurements of these vertical profiles are carried out every few hours during an observation.


Submersing an oceanography instrument from the stern



It is important to determine the underwater acoustic velocity profile, since it changes significantly in time and position.

Effects of the underwater acoustic velocity

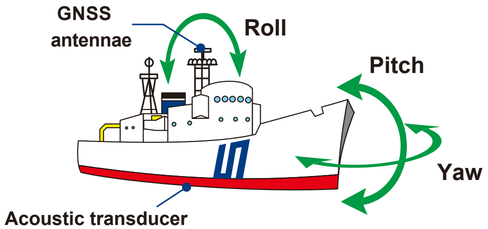
3 GNSS ranging on the vessel

The position of the survey vessel, which is an intermediate point that links the GNSS satellites and the seafloor station, is measured with a precision of few centimeters in 0.5 second interval by a high-precision GNSS antennae mounted on the mast of the vessel. To determine the position of the transducer on bottom of the vessel from the position of the GNSS antennae, the inclination data of the vessel is necessary. Inclination of the vessel due to shaking by waves is expressed as rotations in three directions, which are constantly measured by a dynamic motion sensor in the vessel.

GNSS antenna mounted on the mast of HL 03 *Meiyo*


Measuring the positions of the GNSS antennae and the acoustic transducer

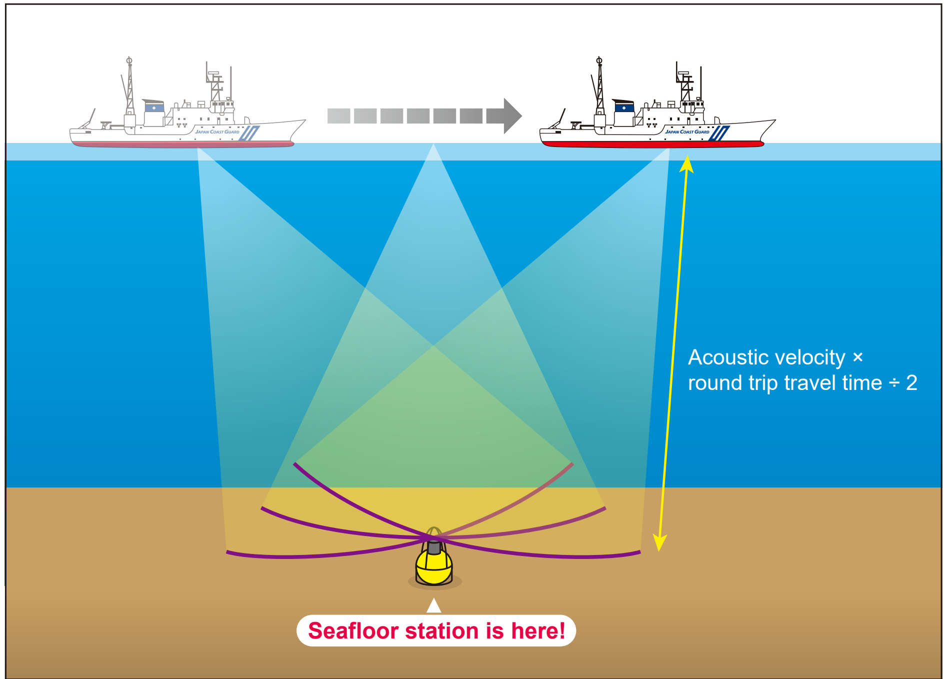
The inclination of the vessel due to constant shaking by waves is measured by a dynamic motion sensor. Inclination is expressed as rotations in three directions. By obtaining these rotations, the accurate position of the acoustic transducer relative to the GNSS antennae can be determined, thus making it possible to accurately determine the position where the acoustic signal is communicated.



Three rotations that express the inclination of the vessel

4 Measurement of the seafloor station position

The precise position of the seafloor station is measured by combining the survey vessel position determined from GNSS ranging, and the range between the transducer and the seafloor station measured by acoustic ranging and acoustic velocity observations.



Determining the position of the seafloor station

Nostalgic scenes

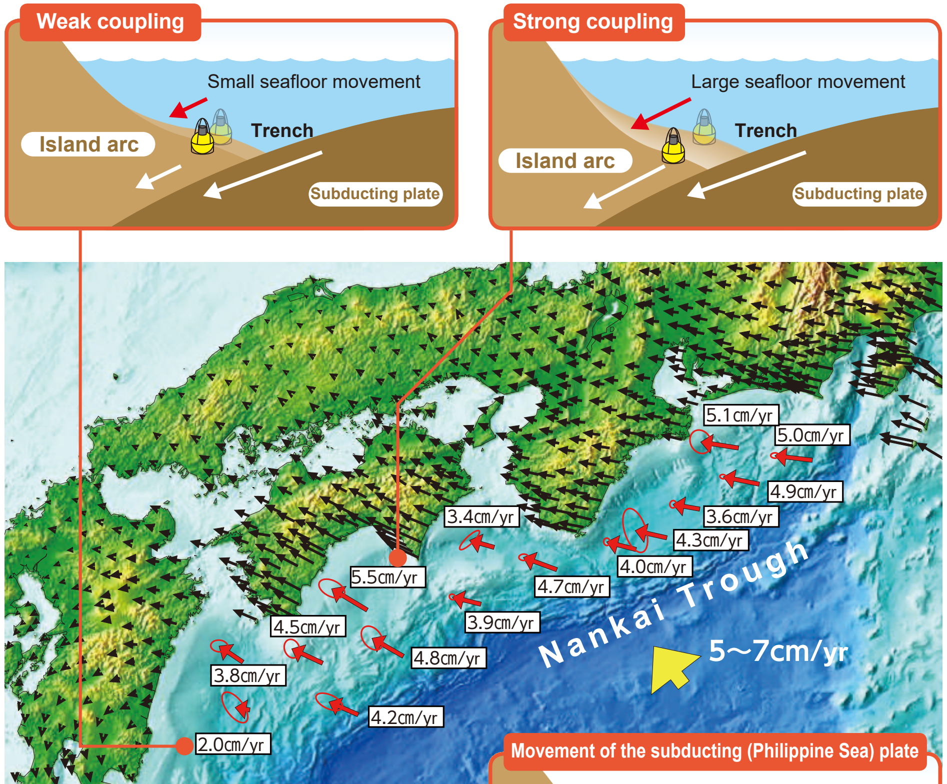
In the early 2000s when the observations were initiated, a pole-like instrument with a GNSS antennae and a transducer on each end was used for observation. This pole was held on the stern of the vessel during an observation.

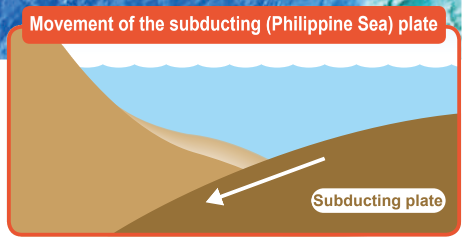
The long pole was bent when the vessel left the port (left picture). The picture on the right is a scene of the routine to hold the pole at the stern. After 2008, the transducer was installed on the bottom of the vessel, making this routine unnecessary.

Achievement
of seafloor geodetic observation

1 Seafloor crustal movement along the Nankai Trough

Japan Coast Guard has been continuously performing GNSS-A observations along the Nankai Trough, where huge earthquakes are expected to occur. From the results of the observations, the distribution of interplate coupling has been revealed for the first time.





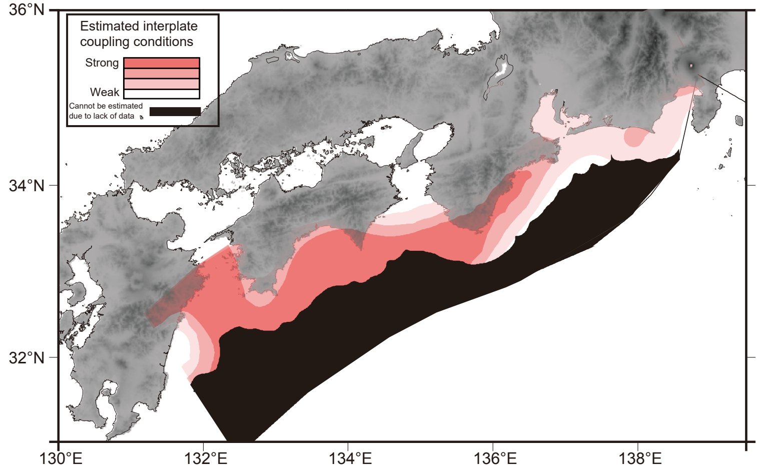
The GNSS (GEONET) observations on land (GSI, black arrows) and the subduction rate of the Philippine Sea plate (DeMets et al. 2010, yellow arrow) are shown for comparison.

Y. Yokota, T. Ishikawa, S. Watanabe, T. Tashiro and A. Asada (2016), Nature, doi:10.1038/nature17632.

2 Interplate coupling estimated from seafloor movements

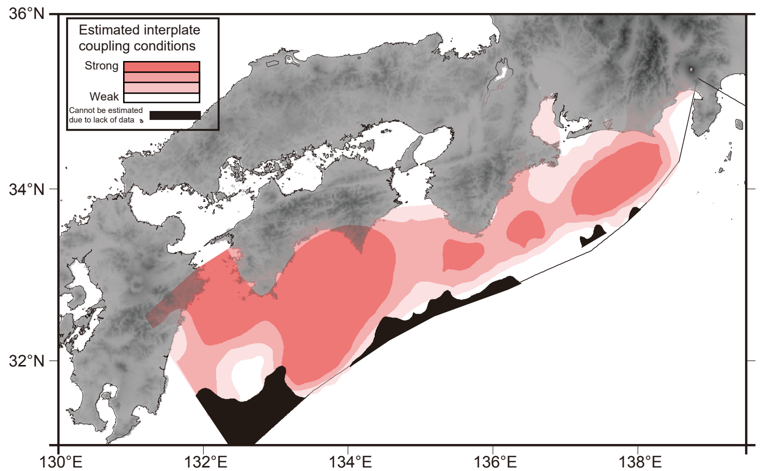
2.1 Interplate coupling estimated from crustal movements on land

We can only estimate the interplate coupling conditions for approximately half of the seafloor from crustal movements of land observed by the GNSS network. This is because the observation points on land are too far from the plate boundary.



2.2 Interplate coupling estimated from seafloor crustal movement

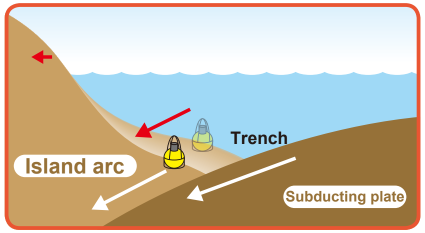
Interplate coupling conditions of large areas can be estimated by employing seafloor crustal movement, as shown in the figure below. The interplate coupling conditions in large areas of the Nankai trough are revealed. However, south regions near the trough axis which are considered to be huge tsunami occurence areas have not been observed yet.

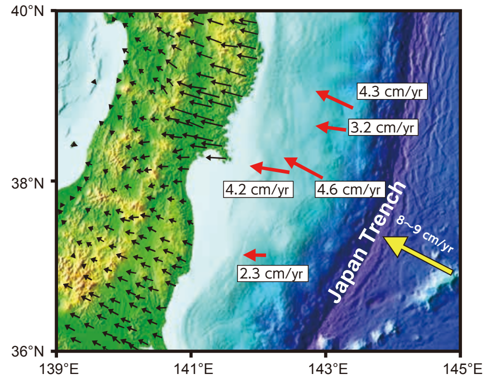


3 Seafloor movements before and after the Tohoku earthquake

3.1 Before the Tohoku earthquake

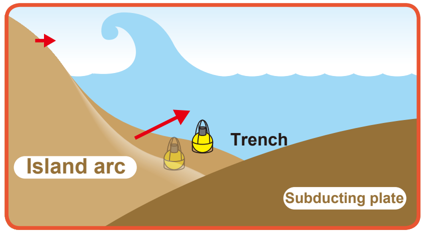
The seafloor movements indicate interplate coupling conditions at the plate boundary.

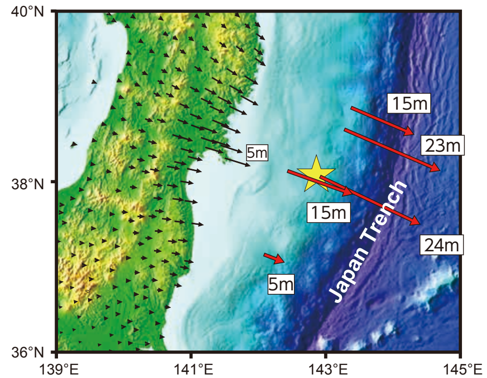




3.2 During the Tohoku earthquake

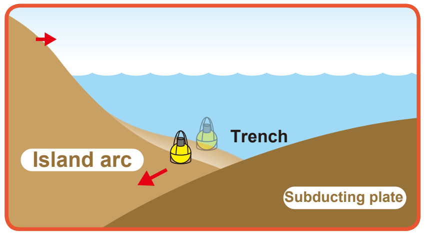
A huge seafloor movement of 24 m was observed on the seafloor. The difference in movement indicates that the epicenter is located offshore in Miyagi.

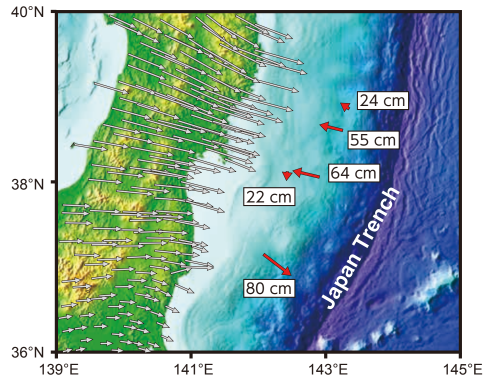




3.3 After the Tohoku earthquake

Complicated movements of the seafloor continue after the earthquake. The difference in movement is thought to be caused not only by the plates but also by the mantle.





M. Sato, T. Ishikawa, N. Ujihara, S. Yoshida, M. Fujita, M. Mochizuki, and A. Asada (2011), Science, doi:10.1126/science.1207401.

S. Watanabe, M. Sato, M. Fujita, T. Ishikawa, Y. Yokota, N. Ujihara, and A. Asada (2014), GRL, doi:10.1002/2014GL061134.