GPS/Acoustic Seafloor Positioning Experiment in the Subduction Zone of the Japan Trench

Hiromi Fujimoto, Satoshi Miura, Aaron Sweeney, Minoru Ito,

Graduate School of Science, Tohoku University Aoba-ku, Sendai, 980-8578, Japan

Yukihito Osada, and Toshihiko Kanazawa

Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, 113-0032, Japan

Abstract

Planning to make in situ observations of seismic coupling and motion of the Pacific Plate near the Japan Trench (about 200 km from the coast), we deployed three precision acoustic transponders (PXPs) in 2001 on both the Pacific plate (70 km from the trench axis at a depth of 5450 m) and the landward slope (70 km from the axis at a depth of 2800 m). The PXP system was developed for the full ocean depth in collaboration with a group at the Scripps Institution of Oceanography. We confirmed precise ranging up to a 15 km slant range with the PXPs. We obtained an accuracy of 2-3 cm for the sea-surface kinematic GPS positioning at a baseline length of 350 km. We have confirmed the anchor stability through visual inspection of PXPs deployed on thick sediment of the old Pacific Plate.

1. Introduction

The Pacific plate is subducted at the Japan Trench at a fast rate of about 9 cm/y. The oceanic plate is moving at a constant speed, but interplate earthquakes caused by the plate motion occur episodically at an interval of tens of years. The seismic coupling coefficient in this region has been estimated to be 20-40% from seismological analysis (Kawasaki et al., 2001). That is, large part of interplate stresses might be released as aseismic slips.

Distribution of seismic coupling in the subduction zone has been estimated from land-based observation of GPS (Nishimura et al., 2000) or seismicity (Igarashi, 2001). According to the analysis by Heki et al. (1997), co-seismic deformation on land associated with 1994 off-Sanriku Earthquake was less than 8 cm, whereas large deformation as large as 1.5 m was estimated on the seafloor. They have also shown that cumulative post-seismic deformation is comparable to the co-seismic slip. However, there has been no *in-situ* observation for these deformations.

Conventional space geodetic technique cannot be directly applied to the seafloor due to strong attenuation of electric waves in the seawater. Combined with underwater acoustic ranging, however, kinematic GPS positioning on the sea surface can be a basis of precise seafloor positioning, which will give us a new insight into the geodynamics in the plate boundaries (e.g., Chadwell et al., 2002). Japan Coast Guard deployed several sets of GPS/Acoustic positioning system on the landward slope of the trenches around Japan. We have also started an experiment both on the landward and seaward slope of the Japan trench to give direct constraint on the seismic coupling at the subduction zone.

2. Measurement system

There are four critical problems in the GPS/ Acoustic positioning based on underwater acoustic ranging and sea surface kinematic GPS positioning. The first and the most critical problem is sub-cm level measurement of two-way travel time of acoustic waves between the sea surface and the bottom. The deeper the seafloor, the more difficult the problem due to larger attenuation of sound waves in the seawater. Acoustic noises near the sea surface make the problem more difficult. We jointly developed a precision acoustic transponder (PXP) system for precise ranging of 10 km, enough to locate a position on the Pacific plate at about 6 km water depth. The electronics and batteries required for operation for more than 5 years are installed in a pressure housing. Signal processing for the system is revised with digital processing from the previous system developed by Spiess et al. (1998). We have also developed compact PXPs with simpler digital processing (Fujimoto et al., 1998) for deployment on the relatively shallow seafloor landward of the Japan trench.

The second problem is long-baseline kinematic GPS positioning. The baseline amounts to 300 km for positioning on a flat seafloor of the Pacific plate. We have successfully tackled this problem with frequency standards both for mobile stations on the sea surface and for land-based reference stations.

The third is correction for the motion of the sea surface platform usually equipped with a hydrophone at the bottom and three or four GPS antennas at the top. A research vessel with reduced acoustic noises is the most appropriate for the platform. Motion of the ship is well monitored with three GPS antennas, because the distance among the antennas is 10 m or more, and period of the motion is much longer than the sampling interval of GPS observation. However, most of the ships available for us in Japan were acoustically noisy. A thruster is necessary to keep the position of the ship, and the thruster usually generates large underwater acoustic noises. That is why we abandoned a ship as a surface platform. We had to adopt a 1.5m or 2m square surface buoy to keep away from the noise sources: thrusters and engines of the ship. A motion sensor and GPS antennas monitor the motion of the buoy. The buoy is connected from the ship with a power cable and a rope of about 100 m. The buoy can be towed with the rope at a speed up to 2 knots against water.

Finally the problem is that two-way travel time must be converted to a slant range. Sound velocity profile is usually obtained from CTD observation. The 4th and most difficult problem results from spatial and temporal variation of sound velocity. Because variation in sound velocity is largest in the top layer of the seawater, the effect can be minimized if 3 or 4 PXPs are uniformly distributed on a circle on the seafloor, and if we keep the position of the surface component near the center of the PXP net. The effect of temporal variations is canceled for the seafloor positioning. We can also detect the effect of spatial variation in the sound velocity. On the other hand, if we try to simultaneously determine with least-square fitting both the sound speed and the positions of PXPs on the seafloor, variations in sound speed result in a systematic shift of the PXP net.

3. Experiments at sea

We examined the PXP system for the deep seafloor during a cruise of the R/V Roger Revelle of SIO near Hawaii Island in October-November 2001. The vessel was excellent enough to keep her position within 1-3 meters from a fixed position with negligibly small acoustic noises under the trade winds of 30 knots. A SIO team deployed 8 new PXPs as well as one of ours for monitoring underwater landslides on the southeastern slope of the island. During the experiment we confirmed precise ranging up to a 14 km slant range with our PXP deployed at 4800m water depth.

We joined KT01-11 cruise of the R/V Tansei-maru, Ocean Research Institute (ORI), University of Tokyo, around the Japan trench in late July 2001. It was a crowded cruise with three other groups for deep-towed surveys, and we allotted 4 days to GPS/Acoustic experiments. We deployed three precision acoustic transponders on the Pacific plate (270 km from the coast, depth around 5450 m). We used a 2-m square surface buoy for GPS/Acoustic observation. The buoy with 3 GPS antennas and a hydrophone was towed with a rope about 80 m away from the R/V Tansei-maru (Fujimoto et al., 2001).

We deployed another set of 3 compact type PXPs on the landward slope (130 km off shore, 2900m deep) of the Japan trench in November 2001 during a cruise of Iwate-maru, Iwate Fisheries Technology Center. We used a 1-m square buoy with 3 GPS marine antennas. The PXPs worked well, but we found that the marine GPS antennas were not good for the kinematic GPS positioning.

It turned out later that the PXPs deployed seaward of the trench had a hardware program. We then deployed three new PXPs from the sea surface and recovered one of the original design with the JAMSTEC ROV Kaiko in July 2002. During the dive, we could visually inspect how the old and new PXPs were deployed on the thick sediment. The original PXPs were each installed on a flat frame of 1m x 1m, and the new PXPs on a frame of 1m x 2m.

We had two more cruises in 2002, and a cruise in 2003, but unfortunately all of them were interrupted by typhoons.

4. Preliminary results

We received good acoustic signals from PXPs at each site. The resolution of the two-way travel time of acoustic signals is preliminarily estimated to be about 1 cm for both the shallow- and deep-water PXP systems. We confirmed precise ranging up to a 15 km slant range with the PXPs developed jointly with the SIO group.

The effect of variations of sound velocity was larger than 1.5 m for the ranging between the sea surface and the PXPs deployed off Hawaii Island. However, the effect is reduced to be a few cm for the positioning of a virtual benchmark in the center of the PXP net.

The position of each antenna on the 2-m square buoy was estimated independently with two different land stations. The RMS residual in the difference is 2-3 cm for the horizontal component (Miura et al., 2002). This error may possibly be an underestimation because common mode noises are removed by differencing. Therefore, we mounted GPS antenna on the perimeter of the 34 m VLBI antenna at Kashima Space Research Center, Communications Research Laboratory. Both the VLBI antenna elevation angle and azimuth are well controlled at the level of a few millimeters. We compared the coordinates of the GPS antenna obtained from KGPS analyses with those determined from the elevation and azimuth log of the VLBI antenna. The preliminary result demonstrates that the residuals from the predicted horizontal position of the GPS antenna are 2 cm RMS (Miura et al., 2002). We expect that the combined GPS/Acoustic technique will be capable of resolving centimeter-level seafloor displacements over the course of a few months.

One of the remaining questions is how well the acoustic transponders are anchored to the old oceanic crust underlying thick sediment. The acoustic transducer is mounted about one meter above the seafloor. If the transponder frame tilts by 1 degree due to differential settling, the horizontal position of the transducer shifts by 1.7 cm. Horizontal motion of the transponder independent of real crustal motion is undesirable. We replaced a PXP with a new one by usin the JAMSTEC ROV Kaiko in July 2002. During the dive, we could visually inspect how the old and new PXPs were deployed on the thick sediment. The old PXP was installed on a flat frame of 1m x 1m, and the new one on a frame of 1m x 2m. The frames were confirmed to be level and buried only 1-2 cm within the sediment. We could confirm that the thick sediment was stable enough to hold each anchor for centimeter-precision geodesy.

We carried a new PXP to a new location about 4 m to the south of an old PXP and measured the relative positions between the two PXPs with a resolution of about 10 cm. This resolution can be improved in a subsequent operation because both PXP frames remain on the seafloor. This demonstrates the feasibility of continuing a precise seafloor geodetic study beyond the lifetime of the original PXPs.

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References

Chadwell, C. D., F. N. Spiess, J. A. Hildebrand, and H. Dragert, Seafloor geodetic evidence

Of episodic spreading 25 km east of the Juan de Fuca Ridge, EOS Transactions, AGU, 83 (47),

F1385, 2002.

Fujimoto, H., S. Miura, Y. Osada, H. Shiobara, T. Kanazawa, A. Sweeney, J. Hildebrand, and D. Chadwell, Deployment of seafloor positioning system for the monitoring of seismic coupling at the Japan Trench off Sanriku, EOS Trans., AGU, **82** (47), p. F283, 2001.

Heki K, S. Miyazaki, H. Tsuji, Silent fault slip following an interplate thrust earthquake at the Japan Trench, Nature, **386** (6625): 595-598, 1997.

Igarashi, T., Plate subduction processes at the northeatern Japan Arc: Studies on data analyses of small earthquakes, Doctor Thesis, The Graduate School of Science, Tohoku University, 116 p., 2001.

Kawasaki I, Asai Y, Tamura Y, Space-time distribution of interplate moment release including slow earthquakes and the seismo-geodetic coupling in the Sanriku-oki region along the Japan trench, Tectonophysics, **330** (3-4): 267-283, 2001

Miura, S., A. Sweeney, H. Fujimoto, H. Osaki, E. Kawai, R. Ichikawa, T. Kondo, Y. Osada, and D. Chadwell, Evaluation of Accuracy in Kinematic GPS Analyses Using a Precision Roving Antenna Platform, EOS Trans., 83(47), F352, 2002.

Nishimura, T., S.S. Miura, K. Tachibana, K. Hashimoto, T. Sato, S. Hori, E. Murakami, T. Kono, K. Nida, M. Mishina, T. Hirasawa, S. Miyazaki, Distribution of seismic coupling on the subducting plate boundary in northeastern Japan inferred from GPS observations, Tectonophysics, 323, 217-238, 2000.

Spiess, F. N., C. D. Chadwell, J. A. Hildebrand, L. E. Young, G. H. Purcell Jr., and H. Dragert, Precise GPS/Acoustic positioning of seafloor reference points for tectonic studies, Phys. Earth, Planet. Inter., **108**, 101-112, 1998.

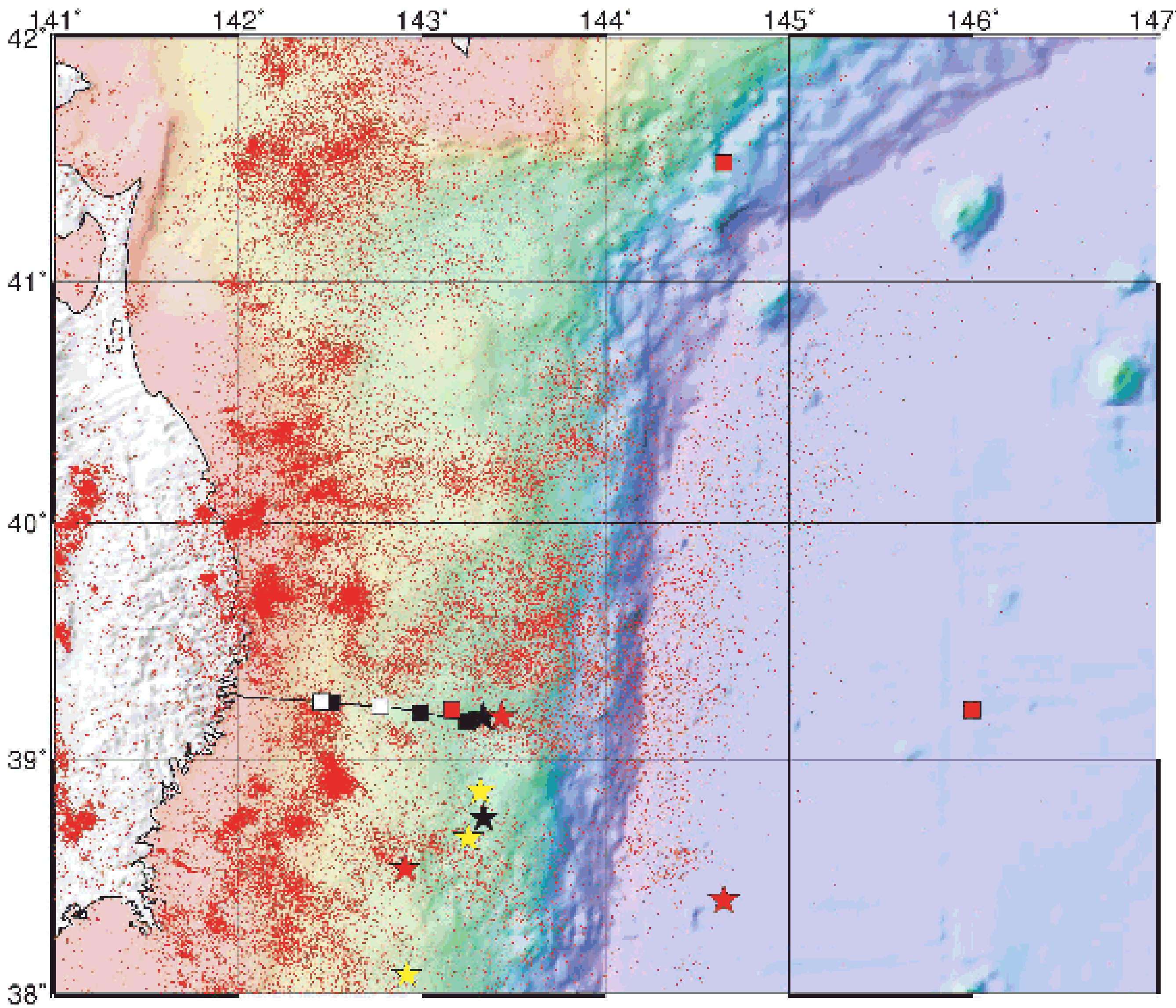

Fig. 1. Observation sites for seafloor geodesy in the subduction zone of the Japan trench.

Seismicity is shown by small dots.

Red stars: GPS/A sites by our group

Yellow stars: GPS/A sites by Japan Coast Guard

Black stars: ODP boreholes with seismometers and tiltmeters

Black squares: Ocean bottom seismometers with an ocean bottom cable

White squares: Ocean bottom pressure recorders with an ocean bottom cable

Red squares: Ocean bottom pressure recorders under the crossover points of TOPEX/Poseidon satellite tracks