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Supporting Online Material for

Displacement Above the Hypocenter of the 2011 Tohoku-Oki Earthquake

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Published 19 May 2011 on *Science* Express
DOI: 10.1126/science.1207401

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Materials and Methods

Seafloor geodetic observation

A schematic picture of the seafloor geodetic observation system that we have developed is shown in Fig. S1. The system measures the ranges from the on-board transducer to the seafloor acoustic transponders through round-trip acoustic travel times, while simultaneously gathering kinematic GPS data. The vessel's attitude is also measured on board by the dynamic motion sensor, which are used to determine the coordinates of the on-board transducer relative to those of the GPS antenna.

By combining the round-trip travel time obtained by acoustic ranging and the positions of the GPS antenna at the moment of acoustic wave emission and reception, we determine the positions of the seafloor transponders. The positions of grouped transponders are finally averaged to a virtual position of the seafloor reference point.

The methodology of our observation technique in detail was described in (*4*).

Using this system, we conducted seafloor geodetic observations at five reference points (Fig. 1; Table S1) about 20 days after the mainshock. Although we acquire acoustic ranging data of about 5,000 shots at a single reference point in a regular campaign, only 1,200~4,000 shots were obtained in the observations after the event at each reference point to cover all the relevant reference points within our limited ship time.

The position reference is Shimosato in central Japan (Fig. 1A), which is located about 800 km southwest of the epicenter of the Tohoku-oki earthquake. We determined positions of terrestrial GPS stations on the coast of Tohoku region, closer to the seafloor reference points, which were actually used as references for kinematic GPS analyses, from Shimosato's reference coordinates. Although Shimosato was also affected by the earthquake, the co-seismic displacement has been observed to be a few centimeters, which is negligible in our present discussion.

Observation errors of this technique are up to several centimeters in regular campaigns. However, for the observations after the earthquake, they are supposed to be about 10~20 cm at MYGI, MYGW and FUKU, and about 50~60 cm at KAMS and KAMN, which are inferred from determined relative positions between multiple transponders at each reference point in comparison with those in regular campaigns before the event. There are three possible causes for this deterioration. First, the number of shots for acoustic ranging at each reference point was fewer than those in regular campaigns as mentioned above. Second, some transponders could have slipped by the strong impact exerted by the earthquake. And lastly, there could have been a local deformation within an array of transponders at each reference point.

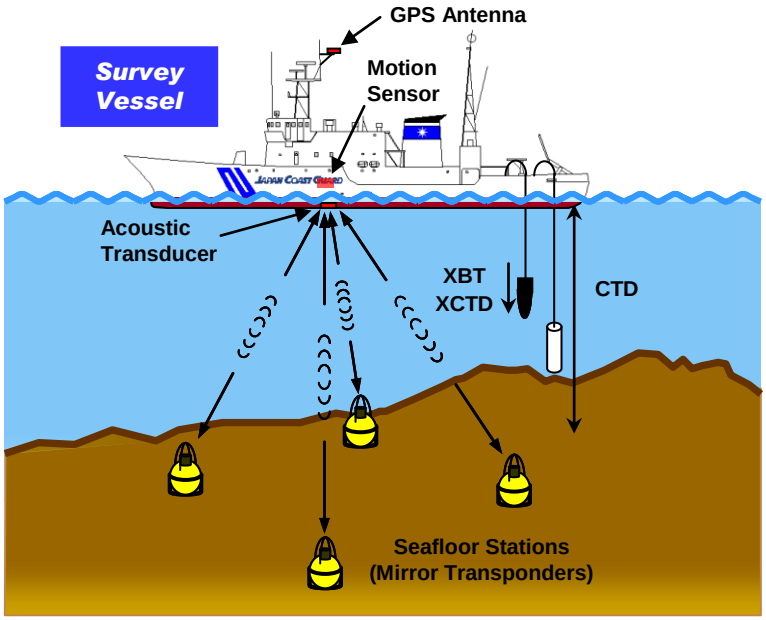

Fig. S1.

Schematic picture of the seafloor geodetic observation system consisting of four acoustic mirror-type transponders at the seafloor and one GPS antenna/receiver, one undersea acoustic transducer and one dynamic motion sensor on-board. A set of four acoustic transponders has been placed on the seafloor at each reference point to form a square whose corners are directed to the north, south, east and west, with a length of the diagonal approximately equal to the mean water depth in the area.

Table S1.

Estimated coordinates of seafloor reference points before and after the 2011 Tohoku-oki earthquake. The coordinates are the averaged positions of grouped transponders.

Site name	Observation date	Latitude			Longitude			Height
		°	′	″	°	′	″	m
KAMN	11/16/2010	38	53	16.740	143	21	43.869	-2306.51
	4/3/2011	38	53	16.551	143	21	44.443	-2304.90
KAMS	11/19/2010	38	38	11.271	143	15	48.021	-2193.21
	4/5/2011	38	38	10.981	143	15	48.893	-2191.72
MYGI	2/21/2011	38	4	51.388	142	54	59.881	-1645.83
	3/28/2011	38	4	51.051	142	55	0.788	-1642.69
MYGW	2/21/2011	38	8	55.897	142	25	59.327	-1044.71
	3/27/2011	38	8	55.734	142	25	59.919	-1045.49
FUKU	2/23/2011	37	9	58.002	142	4	51.233	-1209.47
	3/29/2011	37	9	57.948	142	4	51.412	-1208.61

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