Estimation of seismic wave velocity at seafloor surface and sound source localization based on transmitted wave observation with an ocean bottom seismometer offshore of Kamaishi, Japan

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An *in situ* method of estimating the seismic wave velocity at the seafloor surface by observing the particle motion of a wave transmitted into the sediment is presented; this method uses a sound source whose location is known. Conversely, a sound source localization method using the obtained seismic velocities and involving particle motion observation is also presented. Although this method is applicable only when the sound source exists within the critical incidence angle range, it is expected to contribute to the tracing of vocalizing baleen whales, which are unknown around Japanese waters.

Passive acoustic monitoring with moored or deployed instruments on the seafloor is an advantageous methodology in some respects for surveying vocalizing whales in the ocean, compared with visual survey from ships. It enables long-term observation at a fixed point regardless of weather conditions and does not disturb targets by emitting a noise or by having a presence. In most cases, hydrophones have been used as passive acoustic instruments and hydrophone arrays have been used for the localization of vocalizing whales, which is basic information for understanding their behavior[1-4)]. Low-frequency sounds with a frequency range below 50 Hz that are vocalized by large baleen whales including fin whales can also be detected with ocean bottom seismometers (OBSs)[5-9)]. Recently, at the cabled seismic observatories in the Pacific Ocean off the east coast of Japan, fin whale vocalizations, whose frequency range is 17 – 25 Hz[10)], have been found by the OBSs of the cabled observatories[11)]. At the Kushiro-Tokachi offshore cabled observatory, which has not only OBSs but also hydrophones at the same site, the localization of a vocalizing fin whale was achieved using both the time difference of multipath arrival (TDOMA) of sound pressure data obtained with a hydrophone for horizontal range estimation and the horizontal particle motion obtained with OBSs for the estimation of the azimuth of the sound source[11)]. In other cabled observatories, however, it is not possible to localize the sound sources in the same way, because only OBSs without a hydrophone are attached to the observatories and therefore horizontal range estimation from the TDOMA is not applicable. In Ref. 8, whale localization was conducted by estimating the incidence angle and azimuth of the vocalization signal observed by a single OBS. The incidence angle was estimated from the emergence angle of a wave transmitted into the sediment of the seafloor surface. The problem in estimating the incidence angle, which was used for the estimation of the horizontal range between the OBS and the whale, is that the OBS can only observe the apparent emergence angle of the transmitted wave, which is a composite of a pressure wave (P-wave) and a vertical shear wave (SV wave), which are both converted at the observation site on the seafloor provided that the incidence angle is less than the critical angle. Therefore, the relationship between the incidence angle and the apparent emergence angle depends not only on the difference in P-wave velocity between the water and the sediment of the seafloor surface but also on the S-wave velocity in the sediment. Thus, in order to localize whales, information on the P-wave velocity in both seawater and the sediment and the S-wave velocity in the sediment is necessary, while the seismic velocities, i.e., the P- and S-wave velocities in the sediment, are usually unknown including those at this study site. In Ref. 8, the P-wave velocity was assumed to be 1.8 km/s and the apparent emergence angle was assumed to be equal to the emergence angle of the P-wave in the sediment.

The aim of this study was to estimate the seismic velocities in sediment *in situ* based on the observation of the transmitted wave of an air gun signal using an OBS at the cabled observatory offshore of Kamaishi in Sanriku[12)], one of the cabled observatories in the Pacific Ocean off the east Japan coast.

The cabled observatory offshore of Kamaishi is composed of three OBSs (SOB1, SOB2, and SOB3), each of which has three accelerometers that are placed perpendicularly to one another, similary to the setup at the Kushiro-Tokachi offshore observatory. The X-axis of each OBS is parallel to the cable. The Y- and Z-axes are perpendicular to the cable. However, since their inclinations are arbitrary, these axes are not all vertical or horizontal. Consequently, in order to obtain data on geographical coordinates (north-south, east-west, up-down), raw data (X, Y, Z) must be converted on the basis of the direction of gravity derived from the offsets of acceleration in the raw data and the absolute orientation of the X-axis, as was carried out in Ref. 11. However, the exact orientation of the X-axis has not been confirmed by observation with a remotely operated vehicle as was carried out at the Kushiro-Tokachi offshore observatory. Moreover, it was also unclear whether the coordinate system was right-handed or left-handed. In other words, both the emergent azimuth and the emergence angle of the transmitted wave, which are indispensable information for the localization of a sound source, had an ambiguity when identified using raw waveform data. Therefore, the orientation of the deployed OBSs must first be investigated. With this situation, all pairs, i.e., the four cases of a right-handed / left-handed system with a landward / seaward X-axis, were examined. The waveform data used in this study were obtained at SOB1, whose depth is 2480 m, when the seismic reflection survey with the air gun was carried out along survey line L4 in the KR07-05 cruise of the research vessel (R/V) Kairei. The locations of the observatory and survey line L4 are shown in Fig. 1. The survey line L4 passed 2 km south of SOB1 and 6 km south of SOB2 from east to west. Since SOB2 and SOB3 were not located near enough to L4 to conduct emergence angle observation of the transmitted wave, only the waveform data at SOB1 are discussed in this study. The sampling rate of the waveform data was 100 Hz. First, it was assumed that the orientation of the X-axis was in the east-west direction. By comparing the azimuth of the ship location at SOB1, which was derived from the track data, and the incident azimuth of the air gun signal at SOB1, which was estimated from the horizontal component of the particle motion obtained from the OBS waveform data by principal component analysis[13)], the left-handed system with a landward X-axis proved to be consistent. An example of the three-dimensional particle motion obtained from the OBS waveform data, which was observed at 02:39:41 JST on Apr. 25, 2007, is shown in Fig. 2. The waveform data were band-pass-filtered at a frequency of 5 to 45 Hz to eliminate the offset and low-frequency noise. The dashed line denotes the largest principal axis obtained by the principal component analysis of the particle motion[13], which corresponds to the apparent direction in which the transmitted wave emerged. The horizontal component of the largest principal axis corresponds to the estimated incident azimuth of the air gun signal. The average difference between the azimuth of the ship and that of the incident air gun signal from 02:08 to 03:30 JST was -6°, as shown in Fig. 3. Consequently, the azimuth of the X-axis was estimated to be 276°. A systematic temporal variation of up to 9° was observed from Fig. 3. This may have been caused by the intrinsic property of the OBS, and it is considered that this error will be included in the sound source localization.

In order to estimate the incidence angle of the pressure wave on the seafloor, the vertical profile of the pressure wave (i.e., sound) velocity was calculated in accordance with the UNESCO equation[14] using the water temperature profile obtained from expendable bathythermograph (XBT) data in the KR07-05 cruise and the salinity profile obtained from conductivity, water temperature, and water depth (CTD) data observed by R/V Kofu-maru on May 26, 2007. Both observation sites are also shown in Fig. 1. On the basis of the vertical sound velocity profile and ray tracing results, the relationship between the incidence angle on the seafloor and the horizontal range between SOB1 and R/V Kairei at the sea surface was calculated. Since the inclination of the X-axis of the OBS at SOB1 was estimated to be 2° from the offsets of the acceleration in the raw data, the seafloor was considered to be flat horizontal sediment. The apparent emergence angle of the air gun signal transmitted into the sediment was derived from the vertical component of the largest principal axis shown in Fig. 2. The apparent emergence angle was then associated with the incidence angle on the basis of the corresponding horizontal range between SOB1 and the ship. The result is shown by dots in Fig. 4. The theoretical relationship between the incidence angle and the apparent emergence angle of the plane wave at the liquid-solid interface for various S-wave velocities in the sediment, which was mathematically derived on the basis of Ref. 15, is also shown in Fig. 4. The incident pressure wave velocity in the seawater was estimated to be 1.5 km/s according to the calculated sound velocity profile in the seawater. On the basis of Fig. 4, the critical incidence angle was estimated to be 73°, since the corresponding apparent emergence angle reached 90° and varied abruptly, although there was some ambiguity of less than 3°. Consequently, the P-wave velocity in the sediment was estimated to be 1.6 km/s using Snell's law. The S-wave velocity is between 0.1 and 0.2 km/s from the comparison with the theoretical curves. Accordingly, the S-wave velocity was estimated to be 0.15 km/s.

Conversely, from the theoretical relationship for the plane wave between the apparent emergence angle in the solid and the incidence angle from the liquid at its interface for the seismic wave velocities obtained above, i.e., the P- and S-wave velocities of 1.6 and 0.15 km/s in the sediment, respectively, the incidence angle and accordingly the horizontal range that corresponds to the observed apparent emergence angle in the sediment can be obtained. Combining this horizontal range and the incident azimuth obtained from the horizontal component of particle motion, the sound source, i.e., the ship, can be localized. In Fig. 5, a ship track localized by this method is shown by black dots along with the actual track denoted by gray dots. The localization error was less than 1 km at a distance of 7 km from SOB1, which corresponds to the critical incidence angle of the pressure wave at the seafloor. Similarly to Ref. 8, when the apparent emergence angle was assumed to be equal to the emergence angle of the P-wave in the sediment, which indicates that the S-wave velocity is 0 km/s in Fig. 4, the incidence angle decreased by as much as 5°, allowing us to deduce that the ship location was 200 m nearer than the result shown in Fig. 5. Consequently, the S-wave velocity was not considered to be negligible.

In conclusion, after resolving the orientation of the OBS at SOB1, I presented an *in situ* method of estimating the seismic wave velocity at the seafloor surface by observing the particle motion of a wave transmitted into the sediment, the sound source location of which is known. Conversely, using the obtained parameters and particle motion, a sound source localization method was presented. Although this method is applicable only when the sound source exists within the critical incidence angle range, it is expected to contribute to the tracing of vocalizing baleen whales. This method is planned to be applied to actual whale vocalizations as the next step.

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References

1) K. M. Stafford, S. L. Nieukirk, and C. G. Fox, J. Cetacean Res. Manage. **3**, 65 (2001).
2) D. K. Mellinger, K. M. Stafford, S. E. Moore, R. P. Dzaik, and H. Matsumoto, Oceanography **20**, 36 (2007).
3) S. E. Moore, K. M. Stafford, H. Melling, C. Berchok, O. Wiig, K. M. Kovacs, C. Lydersen, and J. Richter-Menge, Polar Biol. **35**, 475 (2012).
4) T. Tsuchiya, J. Naoi, K. Futa, and T. Kikuchi, Jpn. J. Appl. Phys. **43**, 3193 (2004).
5) R. A. Dunn and O. Hernandez, J. Acoust. Soc. Am. **126**, 1084 (2009).
6) S. D. Frank and A. N. Ferris, J. Acoust. Soc. Am. **130**, 731 (2011).
7) D. C. Soule and W. S. D. Wilcock, J. Acoust. Soc. Am. **133**, 1751 (2013).
8) S. Harris, L. Matias, L. Thomas, J. Harwood, and W. H. Geissler, J. Acoust. Soc. Am. **134**, 3522 (2013).
9) D. C. Brodie and R. A. Dunn, J. Acoust. Soc. Am. **137**, 53 (2015).
10) A. Watkins, P. Tyack, K. E. Moore, and J. E. Bird, J. Acoust. Soc. Am. **82**, 1901 (1987).
11) R. Iwase, Jpn. J. Appl. Phys. **54**, 07HG03 (2015).
12) T. Okada, K. Sakoda, T. Matsuzawa, R. Hino, and A. Hasegawa, Geophys. Res. Lett. **31** L19604 (2004).
13) E. A. Flinn, Proc. IEEE **53**, 1874 (1965).
14) UNESCO, Technical Papers in Marine Science, No. 44 (1983).
15) L. P. Geldart and R. E. Sheriff, *Problems in Exploration Seismology and their Solutions* (Society of Exploration Geophysics, Tulsa, OK, 2004) p. 53.

Figure Captions

Fig. 1. Locations of the OBSs (SOB1, SOB2, SOB3) of the cabled observatory offshore of Kamaishi, track line of R/V Kairei, and observation sites of XBT and CTD.

Fig. 2. (Color online) Example of three-dimensional particle motion at SOB1 observed at 02:39:41 JST on Apr. 25, 2007. The dashed line denotes the largest principal axis.

Fig. 3. Temporal profile of the difference between the orientation of the ship and that of the horizontal component of the particle motion at SOB1 from 02:08 to 03:30 JST on Apr. 25, 2007.

Fig. 4. (Color online) Relationship at the seafloor between the incidence angle of the pressure wave in the seawater and the apparent emergence angle of the wave transmitted into the sediment of the seafloor surface at SOB1. Black dots denote data observed with the OBS and curves denote the theoretical relationship obtained on the basis of the elastic theory. α_2 and β_2 denote P- and S-wave velocities in the sediment, respectively.

Fig. 5. Localized ship tracks (black dots) on the basis of the particle motion observation and actual ship tracks (gray dots).

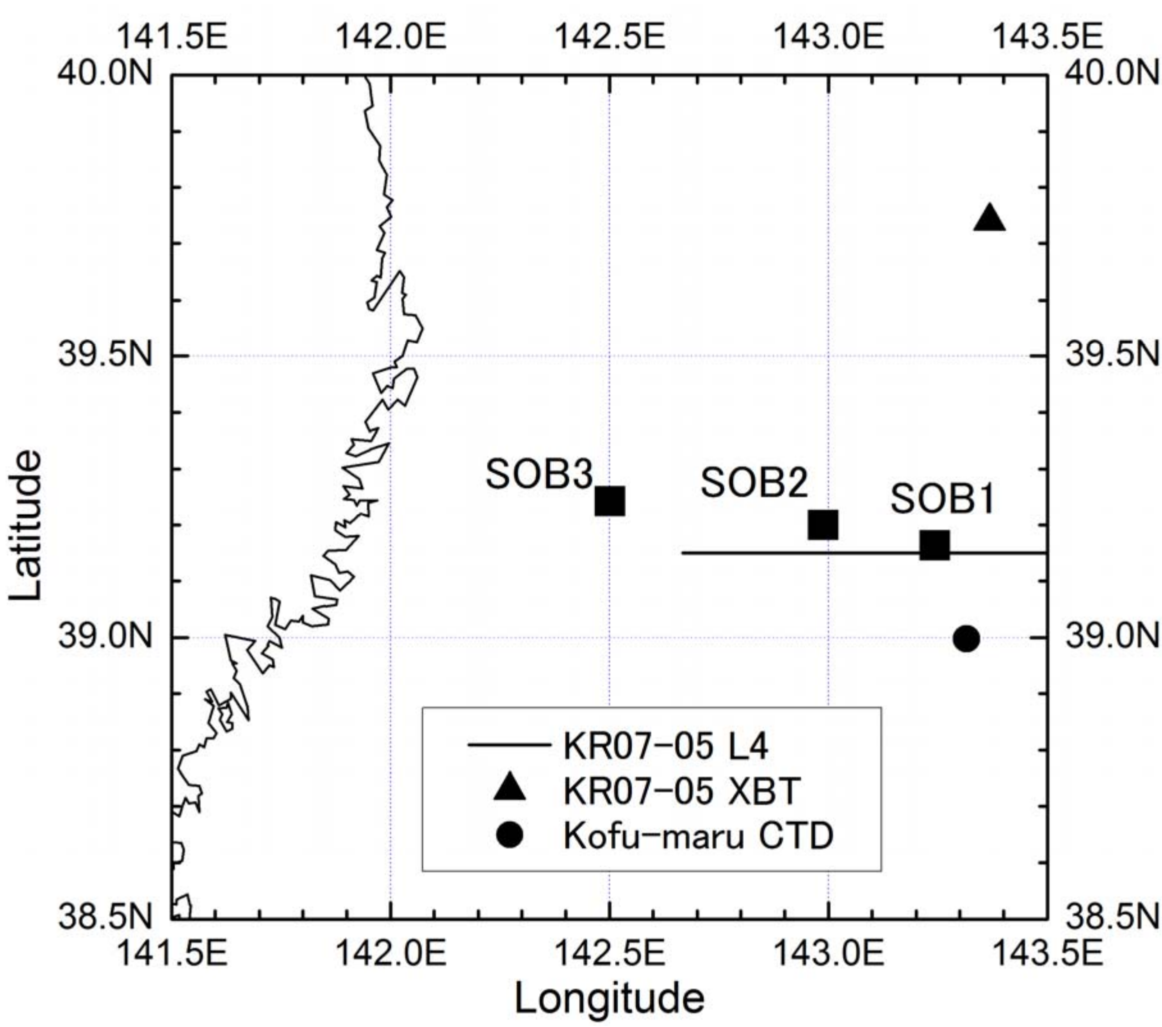

141.5E
142.0E
142.5E
143.0E
143.5E
40.0N
39.5N
39.0N
38.5N
Latitude
Longitude
SOB3
SOB2
SOB1
KR07-05 L4
KR07-05 XBT
Kofu-maru CTD

Fig. 1.

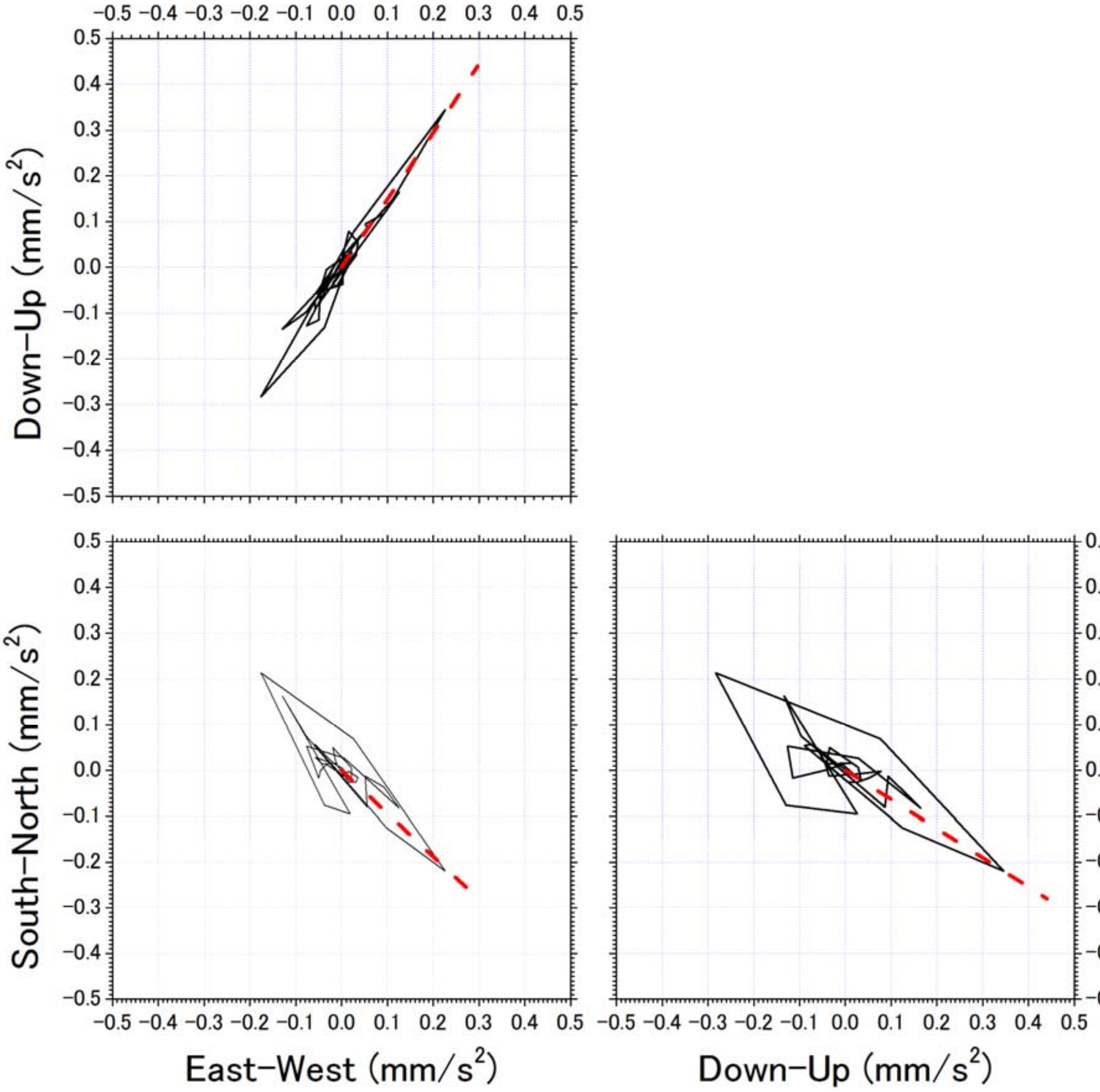
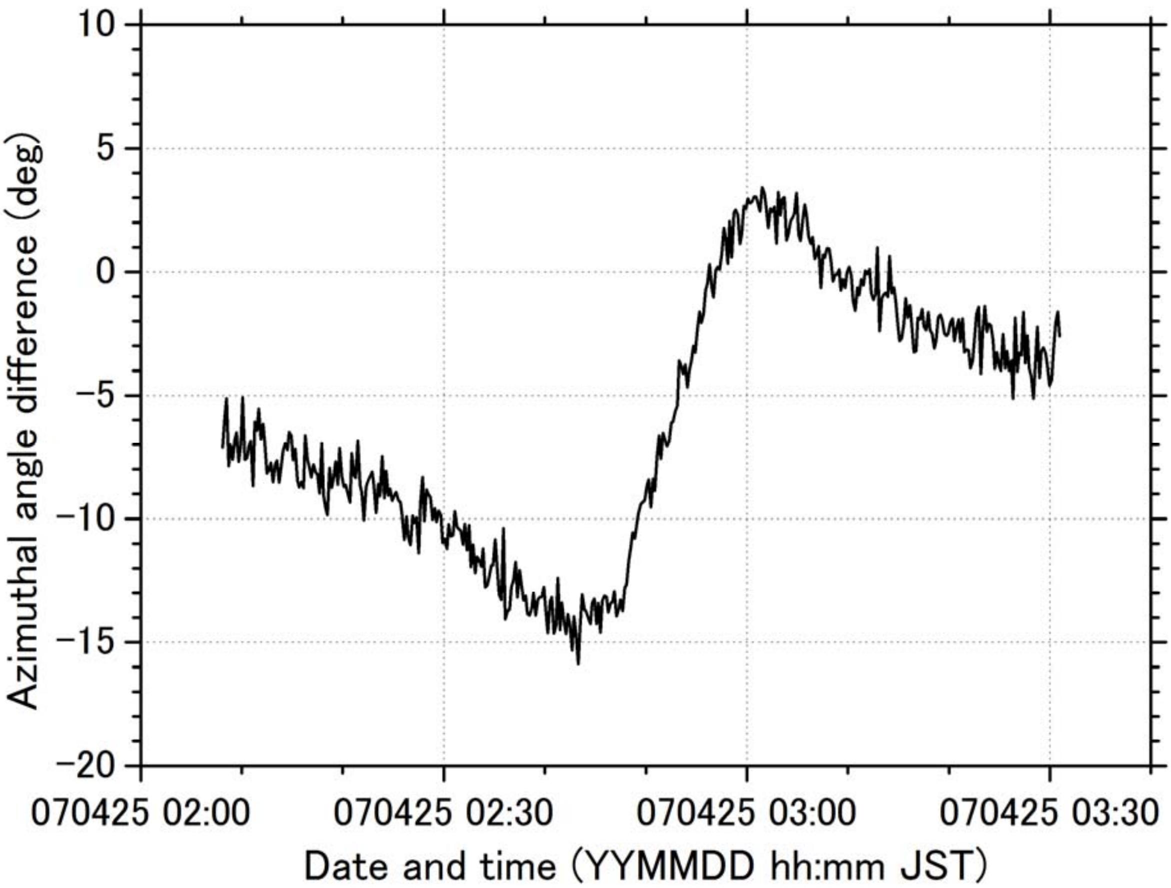


Fig. 2. (Color Online)



10
5
0
−5
−10
−15
−20
Azimuthal angle difference (deg)
070425 02:00
070425 02:30
070425 03:00
070425 03:30
Date and time (YYMMDD hh:mm JST)

Fig. 3.

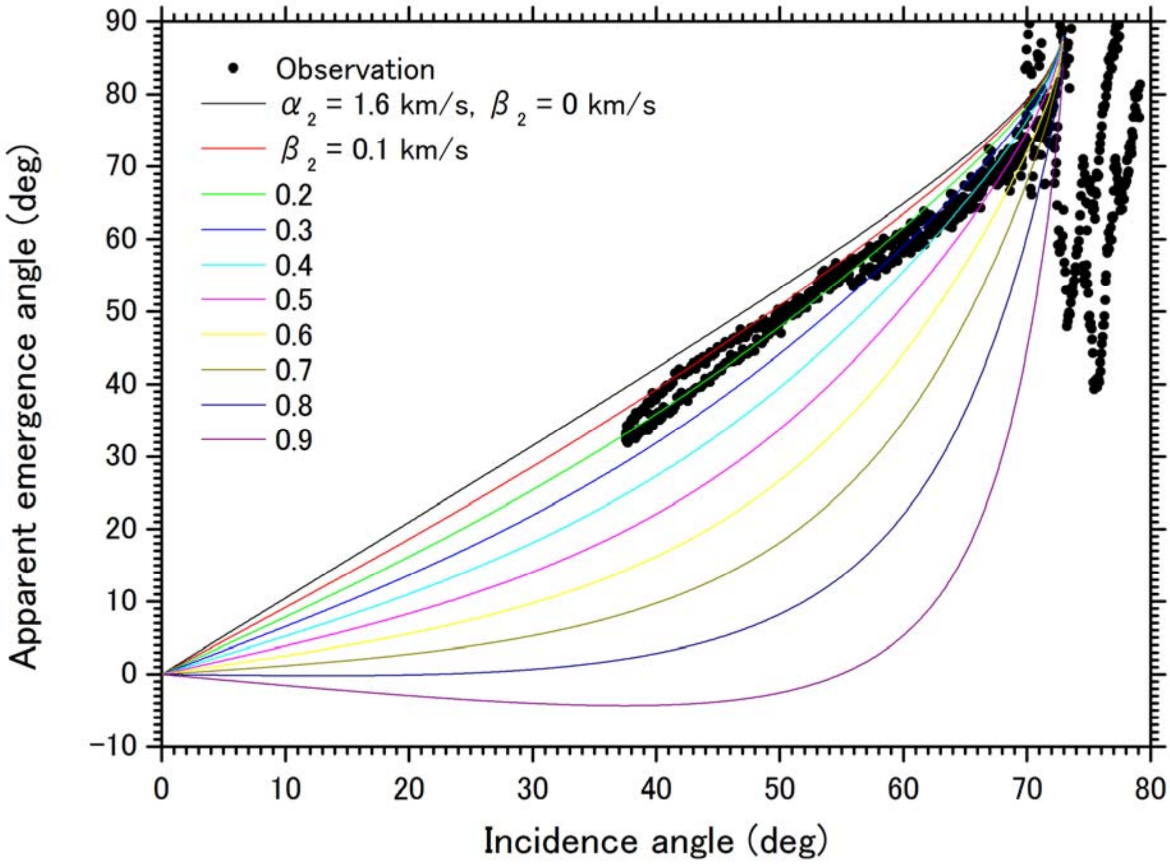


Fig. 4. (Color Online)

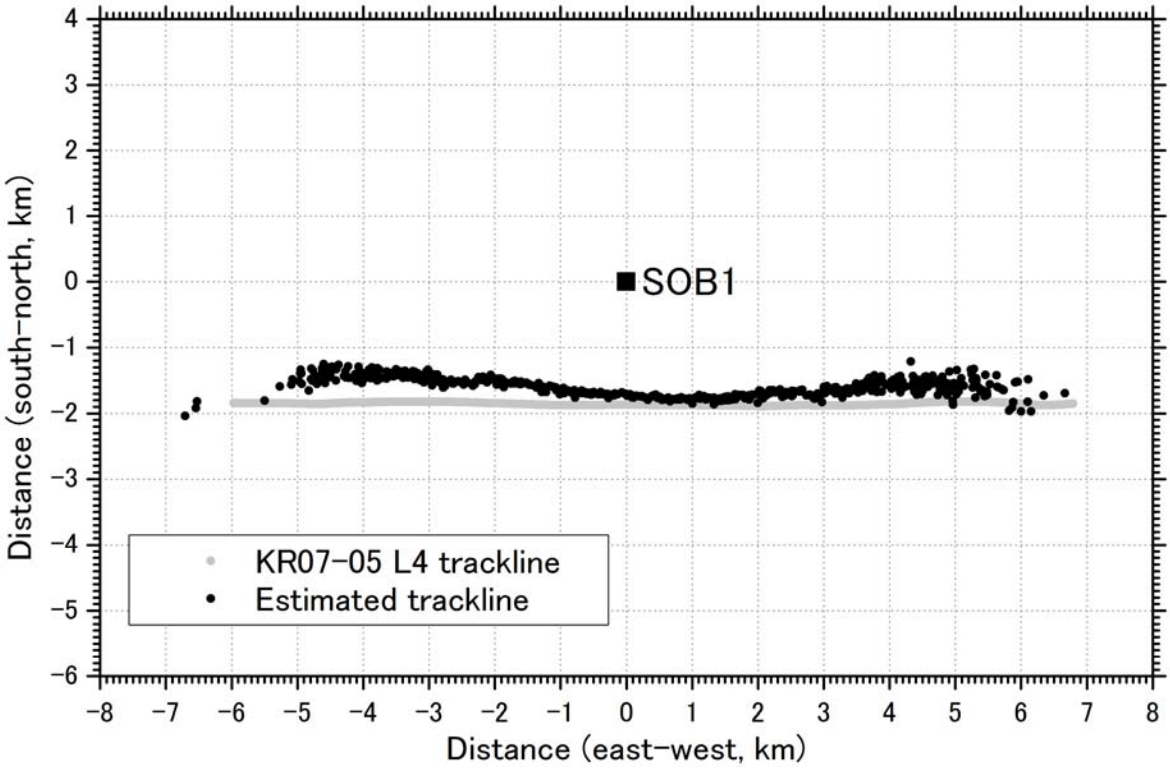

Distance (south−north, km)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
SOB1
KR07−05 L4 trackline
Estimated trackline
−8
−7
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6
7
8
Distance (east−west, km)

Fig. 5.