Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS027-P01 Room:Convention Hall Time:May 23 16:15-18:45

Approximate calculation of group velocity of anisotropic media in the shortest path method

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Shortest path method calculates travel times between sources and receivers by searching the shortest travel time path connecting nodes distributed in the target area. In order to apply this method to anisotropic media, group velocity between two nodes should be calculated. The other part of program is almost same as in isotropic media. In the anisotropic media, phase velocity and group velocity is different. Phase velocity vector and group velocity vector are also different. In weak anisotropic media, the differences are negligible and the difference of ray path due to it is also neglected in general. In this study, we take the difference into account.

At each media node, we calculate group velocity vectors as well as phase velocities in many directions around the node by solving Christoffel equation. We assume six planes around the node. Two components of unit direction vector at the node, parallel to the plane, are two local coordinates on the plane. Grid points are distributed at cross points of the local coordinates. The direction vector is obtained by the group velocity vector, not the phase velocity vector. We fit the group velocities with spline function on each plane and interpolate group velocities at the grid points. The interpolated group velocities are stored and group velocity at the node in arbitrary direction is obtained by linear interpolation of the stored data. In strong anisotropic media, the fitting fails, so that we cannot use this approach.

We add this process into our shortest path method program and apply it to the anisotropic velocity structure of the low velocity layer of PREM model. We get travel times at receivers in horizontal and vertical directions from the source location. The travel tines are same as theoretically expected. The ray paths are little deviated from those in isotropic media. The reason will be that the anisotropy of the PREM is weak.

Keywords: shortest path method, anisotropy, group velocity

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Seismic anisotropy apparently caused by contamination of P-S or S-P converted wave

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Shear wave splitting measurement is a powerful tool for characterizing anisotropy of the crust and mantle. Analysis of shear wave splitting requires records of well-isolated shear waves little contaminated by other phases. Contamination occurs, for example, by sP or SP wave arriving around the expected arrival time of direct s or S in a wide epicentral distance range for a source depth greater than 25km. The consequent waveform distortion of s or S is examined using synthetic seismograms calculated by the Direct Solution Method [Takeuchi et al., 1996] for the model of PREM [Dziewonski and Anderson, 1981]. The synthetics are accurate to a period of 10 sec.

We calculate the synthetics for vertical-dip slip sources placed at 8 depths of 25, 100, 300, 400, 450, 500, 550 and 600 km. For example, the s waveform in an epicentral distance range less than about 5 deg, calculated for the depth of 100 km is contaminated by not only sP but also Rayleigh waves. The waveforms show the arrival of the weak sP and distortion of the radial component by Rayleigh waves. The S arriving at distances larger than about 20 deg is contaminated by SP. The synthetics calculated for the other source depths also show the similar contaminations, the detail of which changes complexly according to the epicentral distance and the source depth. It is difficult to analyze the anisotropy using the direct s or S at periods longer than 10s.

We also examine the cases of ScS and ScS2. For a source depth between 450 and 600 km, the ScP and ScSScP arrive almost simultaneously as the ScS and ScS2, respectively. We use a correlation method for the synthetic ScS and ScS2 phases for the shear wave splitting measurement to see the effect of the ScP and ScSScP. The effect is found to be minor at epicentral distances less than 20 deg, where the amplitudes of ScP and ScSScP are very weak. The effect can be large at the epicentral distances greater than 25 deg. For the shear wave splitting measurement, we have to examine the vertical component and check against the synthetics test more carefully.

Keywords: anisotropy, Shear wave splitting

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Excitation and propagations of seismo-acoustic waves with an open boundary condition

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We developed an efficient numerical method to calculate normal modes of elasto-gravitational planetary bodies with atmosphere and any mechanical dissipation (Kobayashi 2007). Using the method, we can easily calculate eigenfunctions of a solid mode in the atmosphere and those of an atmospheric mode in the solid earth. To show the performance of the method, we calculated a million of acoustic modes including the solid earth and synthetic waveforms of acoustic waves excited by Iwate-Miyagi Nairiku Earthquake (Nagao et al. 2008). We also discussed an effect of zonal winds on the acoustic wave propagations and their waveforms (Kobayashi 2009).

In such a medium, seismic wave energy can escape through the atmosphere and an eigenfrequency of a mode is inevitably a complex number, and any two normal modes are never orthogonal each other even if we use a perfect elastic earth model in calculations. In this presentation, we discussed about excitation problem of normal modes of one dimensional acoustic system as such a dissipative system in the 2010 SSJ fall meeting (Kobayashi 2010). In this presentation, we apply the theory to a realistic coupled system of the solid earth and the atmosphere, and report effects of the open boundary conditions on wave propagations.

Keywords: seismoacoustic waves, excitation, wave propagation, coupling, open boundary, zonal winds

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The Earth's background free oscillation recorded by the laser strain meter beeing in operation at the Kamioka Mine

Wataru Morii[1*], Akito Araya[2], Akiteru Takamori[2], Yasuyuki Kano[1], Hideaki Hayakawa[3], Shuzo Takemoto[4]

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The observations with the two orthogonal laser strain meter of 100m length have carried out since 2003 and are still continuing in a deep tunnel at the Kamioka Mine, Gifu prefecture. Analyzing the laser strain meter record and the barometer record, we investigated the characteristics of the Earth's background free oscillation. We will report the relation between the signal intensity of the Earth's background free oscillation and the atmospheric pressure change.

Keywords: laser strain meter, Earth's background free oscillation, atmospheric pressure change

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Latitude and longitude dependencies of the eigen frequency in core moeds of the earth's free oscillation

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Seismological studies revealed that the inner core had axisymmetric anisotropy(Morelli et al., 1986; Woodhouse et al., 1986).Kawasaki (2009) pointed that the eigen frequency of the core modes changed with the latitude for the axisymmetric anisotropy. In this study, we use waveform data of the 2004 Sumatra-Andaman earthquakes recorded by superconducting gravimeters and STS-1 seismometers. We calculate the power spectrum of the waveform data using discrete Fourier transformation to identify excited core modes and to discuss the latitude and longitude dependencies of the eigen frequency. In addition, we apply Sompi method to excited core modes. Sompi method estimates the eigen frequency and the quality factor of the free oscillation simultaneously.

We identify ${}_0S_0$, ${}_1S_0$ and ${}_3S_2$ as the excited core modes from the power spectrum. We can find the latitude and longitude dependencies in ${}_1S_0$ and ${}_3S_2$, but we can find no dependencies in ${}_0S_0$. From the comparison of the results of Sompi method with those of Fourier transformation, we suggest that the attenuation of the free oscillation affect little the estimation of the eigen frequency.

Because ${}_3S_2$ is sensitive mainly to the boundary between the inner core and the outer core, we suggest that observed dependencies in ${}_3S_2$ are caused in this region. ${}_1S_0$ is sensitive mainly to the outer core.It is unlikely assumed that there is anisotropy in the outer core, because it is difficult to expect lateral variations in density larger than one part in 10^5 in the fluid outer core (Stevenson, 1987). Therefore, the very small dependencies in ${}_1S_0$ may be caused in other sensitive regions that are the core mantle boundary and the inner core. No dependencies in ${}_0S_0$ may result from little sensitivity to the anisotropy of the core and mantle.

Keywords: the earth's free oscillation, spectral analysis, the inner core, anisotropy

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Waveform effects of the thinning or tearing of the subducting Pacific plate beneath Japan

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We studied the detailed distorted structure of the subducting Pacific plate near Honshu in the Kanto district by the use of waveforms from deep earthquakes recorded at fore-arc Hi-net and F-net stations in Japan. Such waveforms confirm most of the earlier observations like dominance of low-frequency onset and following high-frequency energy due to the stochastic waveguide effect of the subducting plate, proposed earlier by Furumura and Kennett (2005). However, new observations for most of the source-receiver paths show the distortion of body waves, when signals traverse the Pacific slab at depths more than 350 km. They include the loss of high frequency energy in P-coda, loss of low-frequency precursor and presence of converted phases in P-coda. Such complexities in the observed waveforms are difficult to explain by existing slab model, indicating sudden lateral change in the wave guiding properties of the subducting slab such as caused by the thinning or tearing of the slab in deeper part.

To explain the observations, we employ two-dimensional finite-difference method (FDM) simulations of complete high-frequency P-SV wave propagation taking thinning of Pacific slab into account. We expect that the observed guided wave energy must decouple from waveguide where the slab is deformed or thin. Low frequency energy leaks out of the slab and travels to the receivers along paths in the low velocity mantle surrounding the slab. Taking into account the tomographic evidence of weak velocity anomaly of the Pacific slab beneath Honshu and the observations of slab tear in the Pacific plate (Obayashi et al., 2009; Kennet and Furumura, 2010), we expect a local velocity anomaly or thinning in the oceanic lithosphere along the Izu-Bonin arc that would be compatible with the observations. The preliminary results, which suggest that the Pacific slab is strongly deformed beneath Honsu, is the cause of the complicated waves from deep events with strong source location dependencies. These effects need to be tested further with a 3-D FDM simulation employing high-performance computers with a variety of possible slab geometries.

Keywords: slab tears, subducting plate, waveguide, wave propagation

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Waveforms of seismic events followed by the 2008 Iwate-Miyagi Inland Earthquake

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It is reported that the 2008 Iwate-Miyagi Inland Earthquake (Mj 7.2) had foreshock activity 40 minutes before the mainshock which occurred at 8:43 on June 14. Two foreshocks at 8:01 (Mj 0.6) and 8:11 (Mj 1.3) less than 1 km apart from the mainshock epicenter are listed in the JMA hypocenter catalog. In this study, we check the waveforms carefully which were recorded at the nearest Hi-net station (Ichinoseki-Nishi, epicentral and hypocentral distances are 3 km and 8 km, respectively), and investigate the foreshock sequence of this earthquake.

We used the waveform of updown component recorded at the Ichinoseki-Nishi station from 7:45 to 8:45 on June 14. We detected by eye 13 events whose initial phases are clear and have large amplitudes compared to noises. Each event has quite similar waveform: every phase such as P, S and reflection phases at the ground arrive at the same time when arranged at the P time. Normalized amplitudes of these phases by those of first P waves are classified into at least two groups by their magnitudes. This fact is thought to reflect that there are various types of focal mechanisms of foreshocks. These features of foreshock waveforms suggest that foreshocks occurred at almost the same place but had more than one fault plane. We will extract the information on change of hypocenter location or heterogeneity structure from the recorded waveforms.

Keywords: 2008 Iwate-Miyagi Inland Earthquake, foreshock, focal mechanism, later phases

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An attempt to detect the inhomogeneous structure beneath the Bungo channel using reflected waves

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In the seismograms observed by stations near the Bungo channel, southwestern Japan, many reflected phases are found. In the previous studies, the shape of the Philippine Sea plate subducting beneath the Bungo channel and the structure of crust have been estimated by using reflected phases in the records of the interplate earthquake (Oda et al., 1990; Ohkura, 2000; Miyoshi and Ishibashi, 2007). We attempted to reveal the inhomogeneous structure from data of a earthquake cluster in the shallower part of the crust.

Assuming horizontal reflectors, we estimated the depth distribution of the reflectors from the differences in travel time between a direct S wave and reflected S wave. The hypocenters were determined by the relative hypocenter determination method (Ito, 1985) in order to reduce some errors. We analyzed only the seismograms having impulsive direct S wave. We use the data at 18 stations including 1 temporal station.

As a result, we recognized the reflected phases in most of the observed seismogram from reflectors in depth range from 15 to 20 km depths. Reflected waves from reflector deeper than 30 km depth were also seen in some traces.

Long-term slow slip events (Hirose et al., 1999; Ozawa et al., 2004) and nonvolcanic deep tremors occurred beneath the Bungo channel. Our result indicates a possibility that the reflected waves from deeper parts have a relationship with these slow earthquakes.

Acknowledgement: We used the seismic data from Kyushu University, the Japan Meteorological Agency, the National Research Institute for Earth Science and Disaster Prevention and Kyoto University.

Keywords: reflect waves, the Bungo channel

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Detecting Subsurface Reflections in Southwestern Japan, Using Ambient Seismic Noise

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We demonstrate to detect several subsurface reflectors in Kinki district, southwestern Japan, using ambient seismic noise. In this area, several subsurface reflectors are reported in previous studies. We computed the auto/cross-correlation functions (ACF/CCF) of continuous short period UD components seismograms obtained from Hinet (NIED), JMA (Japan Meteorological Agency), and DPRI (Kyoto Univ.) seismic networks. We divided the seismic record into 1 hour segments and applied 'running absolute mean normalization' (Bensen et al., 2007, GJI) and band-pass filtering (0.5 - 1.0 Hz). Then we calculated ACFs/CCFs and stacked them for at least 15 months long. At borehole stations whose depths are more than 1000 m, clear 'exotic' phases other than surface waves are observed.

We assumed a 1D model based on the previous result of seismic exploration survey in Kinki district (Hirose and Ito, 2007) and calculated theoretical travel times from Moho and other several crustal discontinuities as well as group velocity of the Rayleigh waves. Travel times of the observed 'exotic' phases are generally explained as signals from subsurface reflectors. At the 2000 m borehole, Moho reflection (PmP) is well identified within 100 km distance as well as other crustal reflections. At station pairs of which distance ranges are greater than 100 km, travel time of 1-st higher mode Rayleigh wave well explains the travel time of the observed exotic phase, however, the amplitude of the observed phase is much larger than that expected from theoretical calculation, which requires further investigation to identify the origin of the phase.

Keywords: Ambient Seismic Noise, Seismic Interferometry, Subcrustal Reflector, Moho discontinuity

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Monitoring of the Nojima Fault structure using ACROSS

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To research the healing process of the Nojima Fault structure which ruptured in the 1995 Hyogo-ken Nanbu earthquake (Kobe earthquake, Mw 6.9), ACROSS was set near the boreholes by the Nojima Fault-zone Probe Project and has been operated intermittently since 2000 to monitor temporal variations of the fault structure. In this study, we investigate the long-term change in the travel time, the amplitude and the anisotropy of the transfer function propagating in the fault fracture zone. The result that the travel time variations in both P- and S-wave arrivals proceed about 2 ms since 2000 are consistent with a healing process of a fault. However, the amplitude does not show interpretable variation. As for the anisotropy, estimated from S-wave splitting, we found that the anisotropy is stable since 2000. The leading S-wave polarized direction (LSPD) in the shallow zone indicates that cracks in this zone are orientated to the strike of branch fault, not the direction of the regional horizontal compression (E-W). The degree of anisotropy in the deep zone is smaller than that in the shallow zone and the cracks in deep zone is close and/or not selectively orientated.

Keywords: ACROSS, monitoring, Nojima fault, S-wave splitting

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Temporal changes of auto-correlation functions accompanied by crustal deformation for the eastern off-Izu seismic swarms

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[1]NIED

In December 2009, a seismic swarm occurred off the east coast of Izu Peninsula, central Japan. The largest earthquakes during the swarm were two events with MJMA ˜ 5.0. For the whole period of the swarm, tilt record changes were observed at stations in the area. Such seismic swarms, accompanied by crustal deformation, occurred often in the region and are likely caused by magma intrusion from depth into the seismogenic crust [e.g., Okada et al., 2000]. NIED has started to record continuous seismic waveforms since 1990s. Recently, temporal changes of auto- and cross-correlation functions were reported before and after seismic and volcanic events in Japan [e.g., Wegler et al., 2009; Maeda et al., 2010] with continuous waveform data. Here we analyzed continuous auto-correlation functions (ACFs) to infer temporal changes of the velocity structure in the eastern off-Izu Peninsula region, before and after seismic swarms accompanied by crustal deformations. We then compare the velocity changes with tilt records, GPS measurements, and seismicity.

We used Hi-net stations to monitor ACFs of continuous seismic records. We divided the continuous waveform data of 100 Hz sampling into segments of 5 minutes length, removed the mean and trend, and applied 1-3 Hz band-pass filtering and one-bit normalization. The ACFs were calculated for each of the 5 minute segments and stacked for time intervals of one week to obtain stable records. The temporal changes of the ACFs versus time are analyzed by considering a reference ACF, which is the mean of the ACFs for a time period without major seismic swarms. The temporal changes of the ACFs were used to calculate the relative fluctuations of the velocity structure (dv/v) following a similar approach with Wegler et al. [2009]. The tilt records were obtained using high sensitivity acceleration seismographs, having the same locations as the Hi-net stations. The records were corrected for the tidal components using the BAYTAP-G software (Tamura et al., 1991). GPS data for this area were provided by GEONET of the Geospatial Information Authority of Japan.

By using the continuous waveform data, we have obtained ACFs since 2002. The record section of ACFs shows that there is a stable phase around 10 s in lag time. The dv/v estimations show a clear decrease associated with significant earthquake swarm activity. The decrease of the dv/v appears to have gradually recovered in several years. Because the noise level did not have specific changes associated with swarm activities except for a short period of several weeks after large events, the systematic velocity fluctuations for a long period detected using ACFs were not caused by changes in the noise characteristics. Crustal deformations detected with tilt record and GPS-measurement also appeared during the earthquake swarms and they correlate with the seismic activity. The processes of the decreases of the dv/v and its recoveries associated with seismic swarms and crustal deformations appeared in the 2006 and the 2009 eastern off-Izu seismic swarms. We interpret the velocity degrease as being caused by magmatic intrusions that are consistent with the crustal deformation measurements. The recovery process after the velocity decrease seems to have a longer time-span compared to the gradual return to the background level of seismicity and crustal deformations. The longer period of velocity recovery might be related to magma cooling processes.

Keywords: Auto-correlation function, temporal change, Izu Peninsula, seismic swarms, crustal deformation

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Detection of seismic velocity changes associated with the 2005 M7.2 Miyagi-Oki Earthquake, NE Japan revealed from seismi

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Seismic intererometry is a one of techniques used to estimate the detailed properties of the Earth interior using vast number of seismic records; a pair of seismic traces is correlated with one another to estimate a Green's functions as a response of subsurface elastic properties (e.g. Campillo and Paul, 2003). Some previous works for seismic interferimetry of ambient noise showed that auto-correlation functions (ACFs) and cross-correlation functions (CCFs) have temporal changes associated with strong motions due to local large earthquakes (e.g. Wegler et al., 2009). Here, we show changes of ACFs calculated from ocean bottom records accompanied with the occurrence of large earthquake. The five ocean bottom seismometers (OBSs) were deployed off Miyagi Prefecture before the 2005 M7.2 Miyagi-Oki Earthquake. All of the OBSs used in this study are a free-fall/pop-up type with a three-component geophone of natural frequency of 1 Hz. We computed ACFs with time-window length of 120 s. Filtered one-hour traces at the frequency band of 0.5?2 Hz were used to compute correlation by one-bit correlation technique. By taking ensemble average of ACFs among 24 hours, the one-day ACFs were computed from June 2005 to February 2006 including the Miyagi event at each station. Computed ACFs showed some common coherent phases throughout observing period. We assumed that computed ACFs reflected subsurface structure just below OBSs.

The phases between 10 s and 15 s in lag time showed slightly delay of approximately 0.1s after the 2005 Miyagi-Oki Earthquake, which are observed at some OBSs. Interestingly, the delayed phases at 15 s in lag time are restored gradually. The delay time of the 0.1 s corresponds to the rate of seismic velocity decrease of 1% if seismic velocity would be uniformly changed around stations after the 2005 Miyagi-Oki Earthquake. The observed seismic velocity change is comparable with the velocity decrease of 1.5% at inland seismic stations, which was reported by Nakahara et al (2007) after the 2005 West Off Fukuoka Prefecture Earthquake (Mj7.0).

Keywords: seismic interferometry, OBS, ACF, the 2005 M7.2 Miyagi-Oki Earthquake

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Search for seismic velocity changes due to the 2009-2010 Bungo-Channel slow slip event with seismic interferometry

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Recently, seismic velocity structures and their temporal changes have been investigated with seismic interferometry, where green function waveforms propagating between two stations are constructed by producing ambient noise correlations of waveform data observed at two stations. Rivet et al. (2010) have reported a possible velocity change of 0.3 % due to the 2006 slow slip event in Guerrero, Mexico. Inspired by their study, we try to detect the possible velocity change due to the 2009-2010 Bungo-Channel slow slip event occurring in southwest Japan with seismic interferometry.

We analyze continuous vertical waveform data obtained at 28 Hi-net stations operated by NIED in the Shikoku region, southwest Japan. Applying band-pass filtering of 0.1-0.5Hz, we first produce 1-day stacked cross-correlation functions (CCFs) for each pair of stations following the running-absolute-mean normalization method (Bensen et al.,2007) to enhance the ambient noise portions. Each 1-day CCF has a similar waveform but the amplitude is changing. Therefore, we produce 1-month stacked CCFs. Stacked CCFs during the whole period for respective pairs show a prominent Rayleigh wave packet propagating with the group velocity of 2.5 km/s. Then, we produce a cross-correlation function between the corresponding phase portions for the 1-month stacked CCF and for the reference CCF, and examine the temporal changes in the arrival time of the phase in 1-month CCF for each station pair.

Even if CCFs are relatively stable in time, say CCFs for stations N.OOTH and N.MISH, they have asymmetry in the CCF delay time, and the phases of Rayleigh wave portion appear in the positive and the negative delay times depending on the season. As previous studies pointed out, this seems to be caused by the temporal change in the distribution or the strength of noise sources. We compare the CCFs for the western and the eastern Shikoku station pairs with those for the northern and the southern ones. The CCFs for the western and the eastern ones show the arrival time seasonal changes of 1 %, and the larger delays appear in winter than in summer if the reference stations are take to be the western ones. Such seasonal delay changes, however, cannot be seen in CCFs for the northern and the southern station pairs. Furthermore, differently from seasonal changes, in some northern and southern station pairs, the CCFs show rapid delays of arrival times amounting to 0.3-0.5 % around January in 2010. The paths between these station pairs sample the region where the 2009-2010 Bungo-Channel slow slip occurs. And the amount of arrival time delays, namely, the reduction of seismic velocity, is comparable to those reported in previous studies. Therefore, the changes in delay times might be related to the slow slip event, though we need further to examine the details in the changes, to distinguish the seasonal changes and to investigate CCFs in some different frequency bands.

In this paper, in addition to the data at the stations in Shikoku, we analyze the data recorded at the Hi-net stations in Ooita and Miyazaki prefectures, the Kyushu region, which give us the CCFs for station pairs whose paths are crossing the Bungo-Channel and well sampling the source region of the slow slip event.

Keywords: Seismic interferometry, ambient noise, cross-correlation, Bungo-Channel slow slip event