Japan Geoscience Union Meeting 2012
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SSS27-01 Room:103 Time:May 23 09:00-09:15

# Fundamental study on estimation of change in local stress field using coda-Q

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In this study, we tested a hypothesis that "coda-Q, i.e., an attenuation parameter for the part of natural earthquake seismogram (called coda-wave) after the S-wave arrival, has a relationship with the state of local stress field in the crust". In the past, it has been discussed that the coda-Q changes before a large earthquake or shows anomalous values around a volcanic zone. However the mechanism causing the change in the coda-Q has yet not been revealed since the coda-Q is considered as a parameter to reflect strong heterogeneity of the medium of seismic wave propagation. In other word, the coda-Q has not been well analyzed to obtain any change of the physical state in the subsurface since the interpretation using the coda-Q is mainly used to interpret the heterogeneity of such medium. We focus on a hypothesis proposed by Aki (2004) pointing out that the prediction of earthquakes is a difficult task since the shallow part of the crust covering earthquake sources is too inhomogeneous, and that the coda-Q could be indicating some preseismic process. In his study, he reported that the seismicity around the San Andreas Fault in California shows high correlation with the variation of the coda-Q inverse around the fault in time. When the seismicity is correlated with the variation of coda-Q, the correlation coefficient becomes higher than 0.8. Therefore, we hypothesize that "the variation of coda-Q has a relationship with the change in the local stress field, which triggers an earthquake". In fact, the coda-Q is reported to show a change before the Southern Hyogo prefecture earthquake in 1995 by Hiramatsu et al. (2000). Their results also imply that the relationship between the stochastic parameter, coda-Q and the state of subsurface medium. This study also supports the hypothesis mentioned above.

To verify our hypothesis, the variation of the coda-Q against the stress was examined using numerical simulation of seismic wave propagation. In this study, we assumed that the coda part of earthquakes would be formed by superposed scattered waves originating from cracks distributed in the medium. We then simulated the coda-wave to estimate the coda-Q for various stress loads. As Okamoto et al. (2010) already reported, the coda-Q varied with respect to the change in the direction and the magnitude of the loaded stress under the condition that the elastic displacement of crack locations were took place due to the loaded stress. The order of the change in the coda-Q against the stress, however, is much smaller than the change in the real data observed by Aki (2004). The calculated change in the coda-Q is only the order of several permill for 10 MPa change in the loaded stress, while observed were tens of percent for earthquakes in California (Aki, 2004). So there should be another mechanism to augment the change in the coda-Q much effectively than the effects of the elastic displacement of cracks. We finally assumed two types of additional effects; (1) phase velocity anisotropy induced by the selective closure and opening of microcracks, and (2) the azimuthal alignment of mezzo-scale cracks. The simulation was done for case that a plane wave travels through the bottom boundary of the model. As a result, we confirmed that the change in coda-Q had a qualitative relationship with the magnitude of the change in the mean normal stress (confining pressure). In addition, the order of the change in the coda-Q agrees with the order of the change of the real data observed in Aki (2004). This result suggests that the magnitude of the stress can be estimated from observation of the coda-Q. Unlike the qualitative relationship between the coda-Q and the crustal stress, the quantitative relationship between them can leads to a new stress monitoring method.

Keywords: Coda-Q, attenuation, anisotropy, stress field, numerical simulation

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# Power-Law Decay of Direct- and Coda-Wave Amplitudes and the Fractal Distribution of Intrinsic Absorbers and Scatterers

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The maximum amplitude of seismic waves of a local earthquake decreases according to some power of distance for a wide range of distance. The coda amplitude of a local earthquake decreases according to some power of lapse time measured from the earthquake origin time. When intrinsic absorbers and scatterers are randomly and homogeneously distributed in space; however, the conventional theory predicts that the direct-wave amplitude exponential decreases with distance increasing and the coda amplitude also exponentially decreases with lapse time increasing in addition to the geometrical decay. The exponential decay of the direct-wave amplitude is inevitable in the case of homogeneous distribution.

This paper presents a theoretical model that leads to the power law decay of the direct-wave amplitude with distance and that of the coda amplitude with lapse time. We can formulate the scattering process in the framework of the radiative transfer theory when the spatial distribution of intrinsic absorbers and isotropic scatterers are fractally random and homogeneous. In the case that their fractal dimension is two, the theory exactly predicts power law decay for both the direct-wave amplitude with distance and coda-wave amplitude with lapse time. An exponential decay term for the fractal dimension 3 changes into a power law decay term for the fractal dimension 2. The difference between the direct- and coda-wave amplitudes and that between their powers are controlled by intrinsic absorption and scattering strength. It will be interesting to measure regional variation and depth dependence in those parameters from the analysis of seismogram envelopes of local earthquakes on the basis of the fractal model in relation with seismotectonic conditions.

Keywords: coda, attenuation, scattering, radiative trasnfer theory, body waves

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SSS27-03 Room:103 Time:May 23 09:30-09:45

# A comparison of finite-frequency and ray approaches in local tomography

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We determined detailed 3-D P and S wave velocity models of the crust in the 1995 Kobe earthquake (M 7.2) area in Southwest Japan using both finite-frequency and ray tomography methods. Our finite-frequency tomography technique is based on the single-scattering theory (Tong et al., 2011). The finite-frequency sensitivity kernel derived in this study reflects correctly the sensitivity of the heterogeneity off the geometrical ray path and the existence of Fresnel volume, and the kernel depends on the dominant frequency of the observed wave. The dominant frequency is estimated directly from the earthquake magnitude based on a relation that is obtained by regressively analyzing the displacement spectra of 20 earthquakes in the study area. We used a great number of P and S wave high-quality arrival-time data from the Kobe aftershocks and other local earthquakes during 2002 to 2010. Our tomographic images obtained with the finite-frequency and ray tomography methods show a high level of similarity, which is verified quantitatively by adopting the structural similarity index. Similar to the previous studies (e.g., Zhao et al., 1996), the present results show that the Kobe mainshock hypocenter is located in a distinctive zone characterized by a high Poisson's ratio and a low product of P- and S-wave velocities, which is interpreted as a fluid-filled, fractured rock matrix that may have triggered the 1995 Kobe earthquake. The crustal fluids in the Kobe hypocenter are considered to originate from the dehydration of the subducting PHS slab beneath Southwest Japan (Zhao et al., 2002, 2010).

Keywords: ray theory, finite-frequency, tomography, crustal structure, earthquakes

SSS27-04 Room:103 Time:May 23 09:45-10:00

# The mechanism of anomalous wave propagating along trench shown by 3D-FDM simulation considering topography and seawater

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To clarify the mechanism of anomalous later phase which appears during shallow earthquake near a trench, we investigate the effect of heterogeneous structures around a trench on generation and conversion of seismic waves by means of numerical simulation using 3D finite difference method (FDM).

During shallow earthquake occurring near a trench (outer-rise earthquake), an anomalous later phase is observed occasionally at stations distant from the epicenter (~1000 km). From the late arrival of the phase, the propagation speed of the phase is estimated as 1~1.5 km/s. The phase has the particle motion like Rayleigh wave, the dominant period of around 10~20 s and the large amplitude. The initial report for the observation of such anomalous phase would be given by Nakanishi et al. (1992), which was about the observation at a station in Hokkaido during the earthquake near the Kuril Trench. After the installation of broadband network F-net, a number of such phases were observed. For example, it appeared at the F-net station AOGF in Izu Islands during 2005 off-Sanriku outer-rise earthquake (Mw 7.0) (Noguchi et al., 2011). It was also found at stations in Kanto region during 2010 Bonin Islands outer-rise earthquake (Mw 7.4). They appear at limited stations located around the junction of trenches. Also, the propagation path for these observations are along the trench. So that the anomalous phase should be attributed to particular propagation path around the trench. For the mechanism of such phenomena, Yomogida et al. (2002) discussed that these phases could be Rayleigh wave trapped along the trench by means of ray tracing. In Noguchi et al. (2011), based on 2D-FDM simulation, we showed that the slow (~1.1 km/s) solid-liquid boundary wave propagates along the deep seafloor, then converted into Rayleigh wave at the seafloor slope and finally observed as an anomalous later phase. In this result, the role of 3D structure around a trench which could trap and convert the boundary wave was not clear.

Based on the result, we conduct the 3D-FDM simulation for the case of AOGF during 2005 off-Sanriku outer-rise earthquake considering the seawater layer, realistic topography and 3D heterogeneous structure. We simulate the seismic wave propagation with the period of longer than 10 s in the area of 900 km x 360km around Japan Trench. We construct 3D structure model using data of the seafloor topography by J-EGG500, subsurface structure by J-SHIS and plate structure by Special Project for Earthquake Disaster Mitigation in Urban Areas. To take the interaction between the seawater and seafloor into account properly, we introduce the calculation method for solid-fluid boundary proposed by Okamoto and Takenaka (2005). As a result, it is clearly simulated that the boundary wave propagating along the seafloor travels a long distance trapped along the Japan Trench axis. It is due to the low velocity zone for the boundary wave caused by the thick seawater along the trench. The boundary wave then escapes the trench at the triple junction at off-Chiba, converted into Rayleigh wave at the seafloor slope, and finally observed as an anomalous phase at AOGF. The result supports the mechanism revealed by 2D simulation, yet it becomes very clear newly that the boundary wave is trapped along trench axis and converted at the trench junction. It is also shown that the relative amplitude of anomalous phase compared to S or Rayleigh phase depends on the hypocentral depth or the relative position of epicenter to the trench. Similar to the other simulations considering water layer (e.g. Maeda et al., 2011), totally, the amplitude and duration of later phase observed onshore become bigger and longer compared to the case without water layer. It would be due to the slow boundary wave trapped in sea area widely for a long time. It indicates that it is necessary to consider the seawater layer when we estimate the ground motion due to the earthquake occurring in sea area.

Keywords: Ocean acoustic wave, Trench trapped wave, FDM simulation, Outer-rise Earthquake, Long period ground motion simulation

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SSS27-05 Room:103 Time:May 23 10:00-10:15

# Encouragement of High Frequency Observational Seismology

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Available frequency ranges for the ordinary observational seismology is limited up to about 30Hz. This limitation is controlled by seismometer's frequency response and/or sampling frequency of data logging system. Why observation frequency is limited up to 30Hz? Interesting phenomenon does not exist above this frequency?

Recently, high speed sampling data logging systems with high dynamic range were developed. In this study, we could use the two high speed sampling data logging systems, which developed by Scimorex Inc. These systems can record contineous 10kHz data sampling with 24 bits resolution, which controlled by GPS timing. We used these data logging systems to observed seismic motions with 1 Hz, 2 Hz eigenfrequency moving coiled velocity seismometers, and over-dumped acceleration seismometer, at Tono region Gifu prefecture, Japan from Dec. 2011. Data amount is not so big, only 3GB/day; for 4 channels with 10kHz sampling.

Fortunately, we could observe the earthquake, which occurred below the Tono region with $M_{JMA}$ = 5.1 (2011/12/14 13:01) and its after shocks. In this study, we have verified the performance of SC-AD10K, and we concluded SC-AD10K has good for observation. Additionally, we will show some interesting observed phenomena, and introduce high frequency observational seismology, and its applicational plan, for example, detailed velocity structure estimation and its velocities monitoring.

We believe more interesting phenomena exist at these frequency ranges. The reasons that past studies did not done at these frequencies are that data logging systems was still developing and observational seismologists feared the amount of data given by high speed data sampling.

Keywords: High speed data logging system, High frequency seismogram, Detailed velocity structure, Seismic wave velocity monitoring

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SSS27-06 Room:103 Time:May 23 10:15-10:30

# Time reversal analysis of seismic waves in Suruga Bay

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We have examined the application of time reversal in the field of the ocean acoustics. A sound pulse is radiated from a sound source set up in the sea, and the sound pulse is received by a hydrophone array set up at the remote position. The sound pulse that converges in the original source location is formed when re-emitting it from the array after time reversal processing is given to the received signal. The waveform of the sound pulse that converges in the source location becomes the same as the waveform of the sound pulse radiated there. The vibration of the hypocenter is obtained by applying this principle.

We pay attention to the earthquake of magnitude 6.5 that occurred in the Suruga Bay central part on August 11, 2009 to examine it more widely.

To obtain the propagating environment that is the most important factor for the application of the time reversal, we proposed the inverse problem method using the robustness of the time reversal.

P wave component is cut out from the received signal by the seismometer, and the time reversal processing is given to it. And, the inverted signal is transmitted in the propagating environment on the propagating simulation. And, the pulse formed in the vicinity of the hypocenter, that is, time reversal pulse is obtained.

As a result, the pulses ware greatly different according to the observation station.

We paid attention to the azimuth, and the time reversal pulse was arranged in an azimuthal order. Even if the range and depth are greatly different it, the time reversal pulse of the observation station which the azimuth is near becomes a similar waveform. However, the waveform of the time reversal pulse has changed greatly when the azimuth is changed. Then, the Fourier transform was performed to the time reversal pulse, and frequency spectrum was obtained. As a result, frequency spectrum of the observation station which the azimuth was near was similar. However, the azimuthal dependence of frequency spectrum appeared greatly. Then, the peak frequency of frequency spectrum to the azimuth was obtained.

When this result is examined from an acoustics standpoint, it is clear that the hypocenter corresponds to not a fixed sound source but the maneuvability sound source.

Keywords: Time reversal,, Phase conjugation, hypocenter vibration, Seismic wave propagation, underwater acoustics

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SSS27-07 Room:103 Time:May 23 10:45-11:00

# Inhomogeneous structure inferred from reflected S waves beneath the Bungo channel, southwest Japan.

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Analysis of reflected phases provides accurate image of structure in deeper region than use of refracted waves. The depth of upper boundary of the Philippine Sea plate subducting beneath the Bungo channel, southwestern Japan has been estimated from the travel time data of the reflected or converted phases observed in the seismic record of the intraplate earthquake (Oda et al., 1990; Miyoshi and Ishibashi 2007). In the seismograms of the crustal earthquakes observed at the stations near the Bungo channel, we found many reflected phases. In this study, we attempted to reveal the inhomogeneous structure in detail by using data of an earthquake cluster in the shallower part of the crust.

After the normal moveout correction, we found the reflected phases in most of the observed seismogram from reflectors in depth range from 15 to 20 km depths under assumption of horizontal reflectors. The waves from the reflector deeper than 30 km depth, which is close to the plate interface, were also seen in some traces.

In order to improve the estimation of the location and the shape of the reflector, we developed a method that minimizes both residuals of travel time data and amplitude ones. Applying the method to the data at SIKH where the distinct phases are observed, we determined the reflector lying not on the plate boundary but near the hypocenter of the non-volcanic tremors. The estimated reflection coefficient implies that the reflector has high impedance contrast to the crustal material. However, the coefficient does not always reliable due to the large variance of data in the estimation. In further study, we should improve the estimation by adding new data set.

Keywords: the Bungo channel, slow earthquakes, amplitude data of reflect phases

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SSS27-08 Room:103 Time:May 23 11:00-11:15

# The characteristics of the surface wave propagation for the 2011 off the Pacific coast of Tohoku earthquake

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In the past decade or so, very dense arrays of strong ground-motion instruments such as the K-NET and the KiK-net have been developed across Japan by the NIED. These networks enable us to visualize the behavior of the seismic wave propagation from large earthquakes. Furumura et al. (2003) examined the seismic radiation and regional propagation characteristics during the 2000 Tottori-ken seibu earthquake (Mw6.6) by means of visualization of wave propagation using data recorded at the K-NET and KiK-net stations. Recovering broadband seismograms from short-period seismograms for the Hi-net data, Maeda et al. (2011) visualized the surface wave propagation for the 2007 Sumatra earthquake. They took into account not only amplitude information but phase information, and found the interference of two surface waves incoming from slightly different arrival directions. The visualization of wave propagation with phase information may have a great potential for revealing the details of wave propagation. In this study, we tried to visualize surface wave propagation with phase information for the 2011 off the Pacific coast of Tohoku earthquake. We used the acceleration waveform data recorded at 525 stations of the K-NET and 628 surface stations of the KiK-net. Considering the mean interval of these stations, we applied a bandpass filter from 0.05 Hz to 0.1 Hz to seismograms and integrated them into velocity waveforms. Then, we made snapshots every one second for each component, and combined them into animation. It was confirmed that some large wave packets concentrically propagated.

In time traces, wave packets with their maximum amplitudes propagated at an apparent group velocity around 3 km/s, which is equivalent to surface wave velocities for such a frequency band. These wave packets were radiated from the source region at ~50 s after the initial rupture, which implies that they were surface waves produced at the second large wave source. Focusing on the wave packets, we found a tear of a surface wave on snapshots at Tohoku region. In order to reveal the cause of this tear, we examined their particle motions. Before making particle motions, we corrected the installation azimuth of accelerographs when needed. From the particle motions, it was revealed that transverse components were predominant in the northeastern area to the tear, whereas radial components were predominant in the southwestern area. Hence, Love wave should be predominant in the northeastern area, and Rayleigh wave in the southwestern area. This result is consistent with theoretical radiation pattern of Love wave and Rayleigh wave (Lay and Wallace, 2002).

Acknowledgment: The strong motion records of K-NET and KiK-net (NIED) were used for the analysis. We thank Prof. Tomotaka Iwata and Dr. Kimiyuki Asano (DPRI, Kyoto to Univ.) and Dr. Takuto Maeda (CIDIR, Univ. of Tokyo) who provided the helpful information.

Keywords: surface wave, visualization, the 2011 off the Pacific coast of Tohoku earthquake, radiation pattern

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SSS27-09 Room:103 Time:May 23 11:15-11:45

# Seismic interferometry in exploration geophysics: a review from practical aspect

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This is a brief review of the seismic interferometry (SI) in an exploration geophysics. The SI has highly developed and become multifunctional in this decade. Many theoretical and application researches have been published. In a view point of the exploration, an interferometric redatuming from a controlled-source seismic observation is one of the most important use. For example, a walkaway VSP survey can be changed to a reflection survey with sources and receivers on a well, which could image vertical structures clearer than a conventional surface reflection survey. Additionally, extracting signals from a passive seismic data is also useful to estimate subsurface structures or rock properties. The ambient noise surface wave tomography is based on the SI technique to generating Green functions from passive seismic data. A pseudo reflection survey from local earthquakes has capability to profile regional subsurface structures using not only S-wave coda but also P-wave coda.

The basis of the SI is an amplitude summation at stationary points after phase shift by crosscorrelating the seismic traces of the data with many sources or of the long passive seismic data. I summarize key terms at four practical aspects for effective use.

[1] Seismic source
(a) Controlled-source (air-gun, vibrator, dynamite, and so on)
(b) Natural earthquake
(c) Natural/artifitial ambient seismic noise
[2] Method
(a) Cross-correlation
(b) Deconvolution
(c) Multi-dimensional deconvolution
(d) Cross-coherency
(e) Convolution
[3] Function
(a) Redatuming
(b) Data interpolation/extrapolation
(c) Signal extraction
[4] Objective
(a) Reflection seismic imaging
(c) Surface wave tomography / inversion
(d) Rock property estimation
(b) Data processing; signal enhancement, noise elimination

Keywords: seismic interferometry, exploration geophysics, controlled-source, redatuming, passive seismic, signal extraction

SSS27-10 Room:103 Time:May 23 11:45-12:00

# Discussion on the significance of seismic interferometry to estimate inclined layered medium

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In a case where the spatial auto-correlation (SPAC) method (Aki, 1957) is used to estimate phase velocity, the underground structure is assumed to be horizontal layers, which confine the estimation accuracy. On the other hand, according to seismic interferometry theory, in an elastic medium the Fourier transform of azimuthal average of the cross correlation of motion between two sites is proportional to the imaginary part of the exact Green's function between these site (SanchezSesma, 2006). It means that it is possible to introduce the concept of Green's function to SPAC method because we calculate out many Fourier transform of cross correlation as intermediate results. Actually, there was a successful example combining the H/V method and seismic interferometry by Sanchez-Sesma before. Hence, we propose a method combining the conventional SPAC method and the concept of Green's function, which is known as the seismic interferometry in frequency domain. It is expected to obtain more accurate model of ground structure like inclined layered medium.

Afterwards, we take the ratio of power spectra of center of the array and one site on the circular array to calculate the ratio of imaginary part of Green's functions of these sites. Therefore, in practical observations, we calculate the ratio of power spectra of center of the array and one site on the circular array to obtain the ratio of imaginary part of Green's function of these sites. The ratio of Green's function can be obtained without any additional calculation, because the power spectra are just intermediate results in the process of the SPAC method. Then, we can modify the structure, such as the thickness of each layer, to satisfy the ratio of the imaginary part of Green's function. Therefore, more detailed information of ground structure such as inclination can be obtained from the combination of the SPAC method and seismic interferometry. The condition to satisfy this method is the diffusive wavefield.

In order to examine the validity of the proposed method, we do the sensitivity analysis and numerical simulation. In sensitivity analysis, we calculated the ratio of imaginary part of Green's function between varieties of 2-layered models with different thicknesses and see how the ratio varies with the thickness. Through 36 comparisons between 36 pairs of models, it is found that the shallower ground structure is, the more sensitive the ratio is with respect to the thickness. In numerical simulation, we use certain finite difference method-based program to simulate the diffusive wavefield by random sources and see how the ratio of power spectra matches the ratio of imaginary part of Green's function. Through 12 comparisons, it is found that the critical frequency which gives the peak value of ratio matches quite well. Through error analysis, it is found that the shallower structure is, the smaller error is.

In conclusion, the validity of proposed method is primarily confirmed. It has best accuracy in estimating shallow structure.

Keywords: Seismic Interferometry, Green's function, Cross spectrum, layered medium, SPAC method

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# Structure imaging by cross-correlation of local earthquake records: Simulation on source distribution and artifacts

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Seismic interferometry synthesizes a seismic response (often called a virtual shot record) that would be recorded at one receiver as if there was a source at the other receiver location by cross-correlating the seismic traces observed at two receivers. This operation is equivalent to retrieving surface-related reflections. By applying the method to natural local earthquake records observed at a dense receiver array, we can simulate a seismic reflection survey of crustal scale without any artificial sources. Subsurface imaging can be accomplished by adopting highly advanced data processing and imaging technology of reflection seismology to the virtual shot records. In order to synthesize virtual shot records with sufficient accuracy, the assumption of seismic interferometry that sources are distributed densely and uniformly in space should be satisfied. However, the lopsided distribution of the hypocenter of natural earthquakes may result in lowering signal-to-noise ratio of the synthesized virtual shot records and generating artifacts on the seismic profiles.

In this study, numerical experiments were conducted regarding the accuracy and reliability of seismic interferometry using local earthquake records for imaging crustal structure. Following three points were investigated: 1) the influence of lopsided source distribution of natural earthquakes on the virtual shot records and the imaged profiles, 2) the source-receiver geometry that is effective for imaging the target crustal structures, and 3) the origin of artifacts and the way to suppress them. A 2-D model simulates subsurface structures beneath Tokai region in central Japan including crustal structures and subducting oceanic plate. The model is defined by 100 km x 50 km in the horizontal and the vertical direction. The survey line is subparallel to the convergence direction of the Philippine Sea plate. Using the sources distributed in shallow crust, deeper crust, oceanic slab and continental slab, 125 SH-wave seismograms were calculated in total.

As the results, the accuracy of the virtual shot records improves as the number of the sources (earthquakes) increases. The quality of the records depends on the spatial relation among the sources, the receivers and target reflector. Particular combinations of the sources and the receivers were found effective to synthesize virtual reflection records with fewer sources. Such source-target-receiver geometry is consistent with the concept of stationary phase that has been theoretically derived by previous studies. Imaging the target structures is possible as long as the geometry is retained even if the earthquake sources are not necessarily distributed uniformly, nor the range and number of the receivers are limited. The depth-migrated profile obtained using earthquakes distributed in the continental slab and oceanic slab shows good illumination to the target structures from shallow to deep area. The study shows that some particular type of artifacts are dependent on the source depth. Such depth-dependent artifacts in the migrated profiles can be suppressed by increasing the source depth variation.

Keywords: seismic wave, scattering, interferometry, crustal structure, imaging, simulation

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SSS27-12 Room:103 Time:May 23 13:45-14:00

# Seismic anisotropy from the interferometric analysis of seafloor records

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The seismic interferometry is now widely applied to the ambient noise source in continental regions [e.g. Shapiro et al., 2005] and in an oceanic region, the East Pacific Rise (EPR). Harmon et al. [2007] used the vertical components of ocean bottom seismometers deployed in the EPR region for analyzing the Rayleigh wave. In this study, we apply similar method to the three-component record of broadband ocean bottom seismometers (BBOBSs) deployed in (i) the Shikoku Basin (SB) region by the Stagnant Slab Project and (ii) the French Polynesia (FP) region by the TIARES (tomographic investigation by seafloor array experiment for Society hotspot) project. The spacing of the stations is about 100-200 km. For each region, we obtain the phase velocities of (i) the fundamental mode of Rayleigh wave (14-29 sec), (ii) the first higher mode (5-11 sec) of Rayleigh wave, and (iii) the fundamental mode of Love wave (2.5-14 sec) by the SPAC method [Aki, 1957]. The propagation of the first higher mode of Rayleigh wave appears (i) in the horizontal component (7-11 sec) for the SB region, (ii) in both vertical and horizontal components (5-10 sec) for the FP region, and (iii) in the vertical component (3.5-7 sec) for the EPR region. The difference between EPR and SB regions can be interpreted by the difference between the periods of analysis. To account for the difference between FP and SB regions, on the other hand, we need to discuss other causes such as the difference of sedimental thickness and the source intensity of ambient noise.

By further using the phase velocities measured by array analysis of teleseismic waveforms, we obtain one-dimensional radially anisotropic structures at the uppermost mantle beneath SB and FP regions. Both structures show that the velocity of horizontally propagating shear-wave with horizontal polarization ($V_{SH}$) is 3 % higher than that with vertical polarization ($V_{SV}$). We also focus on the azimuthal anisotropy. By the analysis of teleseismic waveforms, the phase velocity (30-50 sec) beneath the FP region is revealed to depend on the back-azimuth, t, in a form with sin(2t) and cos(2t). We obtain consistent pattern at shorter periods (20-30 sec) by the ambient noise interferometry with assuming homogeneous structure beneath the array. We will discuss the effects of inhomogeneous structure and inhomogeneous source distribution, and will estimate the azimuthal dependence at shorter periods.

Keywords: Seismic interferometry, ambient noise, anisotropy

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# Detecting Temporal Evolution of the Subsurface Structure Associated with the 2011 Tohoku Earthquake Using Ambient Noise

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Temporal variation of the seismic wave velocity in central - eastern Japan associated with the 2011 off the Pacific coast of Tohoku Earthquake was preliminarily investigated using ambient seismic noise. Vertical components of the continuous seismic waveforms recorded by the seismic networks operated by NIED (Hi-net), JMA (Japan Meteorological Agency), and DPRI (Kyoto Univ.) were used for analysis. Cross-correlation functions (CCF) of 0.1Hz - 1.0Hz and 1.0 Hz - 2.0Hz frequency bands among station pairs whose separations are less than 120 km are calculated. CCFs from January 2011 to June 2011 are calculated and the temporal change of the lag times of the Rayleigh wave arrivals are compared. Auto-correlation functions (ACF) of 2.0Hz - 10.0Hz frequency band are also calculated for each single day for each station. Preliminary result of the CCFs show that the regions of velocity decrease are observed along the Pacific coast in the NE Japan, where experienced the strong ground motion at the mainshock, especially in the 0.1Hz-1.0Hz frequency band. However, CCFs in the Chubu district, where experienced no strong ground motion, exhibit no clear velocity changes in the CCFs of both frequency bands. Theoretical static strain change associated with the mainshock in the studied area is more than $10^{-5}$ large and velocity change associated with strain change was expected. The observed facts probably indicate that lagtime change in CCFs are caused by strong ground motion rather than strain changes. On the other hand, ACFs at several stations in both NE Japan and Chubu district clearly exhibit lagtime change that indicate subsurface velocity decrease. Observed feature in the ACFs in rather remote area are likely caused by not direct effect of strain change but indirect effect such as ground water level change caused by strain change, which is previously reported by Savage and Ohmi (2010, AGU FM).

Keywords: 2011 off the Pacific Coast of Tohoku Earthquake, Cross-correlation of ambient noise, Temporal change of subsurface structure

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SSS27-14 Room:103 Time:May 23 14:15-14:30

# Seismic velocity reduction after the 2011 Tohoku-Oki earthquake using repeating earthquake

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We used repeating earthquakes data to estimate velocity change in the overriding plate from Kanto to Hokkaido region associated with the 2011 M9.0 Tohoku-Oki earthquake. Because repeating earthquakes occur as the repeating slips on the same patch on the Pacific plate with the same source mechanism at different time, waveform data of repeating earthquake is suitable for detecting temporal change in subsurface structure.

First, we performed the moving window cross-spectral analysis for vertical component of seismograms of 54 repeating earthquake sequences. Before the analysis, data were filtered with a band-pass window of 1-10Hz. To align the arrival time of P-wave, we used cross-correlation for the P-wave in a 5-sec time window centered by computed arrival time according to the 1-D structure of JMA2001 [Ueno et al., 2002]. After aligning the P-wave, we computed cross-spectra for the moving time window with a length of 2-sec at every 0.1 sec to measure time-shift between a pair of repeating earthquakes. For pairs of repeating earthquakes that are both before the 2011 Tohoku-Oki earthquake, the time-shifts are almost zero from direct P-wave to S coda. In contrast, for pairs before and after the earthquake, the time delay gradually increases with lapse time. This result indicates the velocity decrease after the 2011 Tohoku-Oki earthquake. For example, at a Hi-net station (N.KAKH) near the Oshika Peninsula, the time delay linearly increase just after P arrival to about 0.02 sec in 40 sec for an repeating earthquake sequence of which epicentral distance is 232 km. From the slope of the time delay, the amplitude of velocity reduction is about 0.05 %. The time delay does not always show linear increase with lapse time. The behavior of the time delay seems to depend on the location of event-station pair, which means heterogeneous distribution of velocity change.

Secondly, we only used the information of direct part of a seismogram to estimate the location of the velocity reduction. This is because the time-shift in direct part simply reflects the velocity change only along a direct ray path in contrast to the complex path of coda waves. One problem for using the direct part is an error of origin time. However, because the errors of origin times are identical at all stations, we can estimate the relative delay in many stations for a pair of repeating earthquakes that can be used for the estimation of the spatial variation of time-shift in direct part. In order to evaluate the spatial variation of time-shift for a pair of repeating earthquakes, we subtract a median of the time-shifts of direct P-wave for all stations from the time-shifts of P and S-wave at every station. From the result of all repeating earthquake sequences, we can recognize clear relative time-delay of about 0.01 sec for S-wave by in both the fore-arc and back-arc region from Fukushima to Iwate prefecture. Furthermore, we estimated spatial distribution of the S-wave velocity change by a tomographic inversion method using the time-shift as input data. In this inversion method, we solved slowness changes in three-dimensional blocks and the errors of the origin times simulatenously. The ray path is computed by using the JMA2001. As a preliminary result, a major slowness increase (velocity decrease) of 0.05 % is estimated in upper crust in Tohoku region from Fukushima to Iwate prefecture. The receiver-side velocity reduction can be interpreted as the damage in near surface due to strong motion or the static stress change due to coseismic slip on the fault.

SSS27-15 Room:103 Time:May 23 14:30-14:45

# Temporal change in shallow subsurface structure detected by coda wave interferometry

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Understanding of shallow subsurface structure is important for prediction of earthquake strong motion, elucidation of transport process of underground water, and so on. On the other hand, recent progress in theoretical and observational researches on seismic interferometry reveal the possibility to detect subtle ($<$ 1%) change in subsurface seismic velocity. This high sensitivity of seismic interferometry to the medium properties may thus one of the important ways to directly observe the time-lapse behavior of shallow crustal structure. In this presentation, we report the long-term variation of subsurface velocity and co-/post-seismic change associated with the 2011 off the Pacific coast of Tohoku earthquake revealed by applying the coda wave interferometry to the NIED KiK-net data.

In this study, we use the acceleration data recorded at KiK-net stations operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). Each KiK-net station has a borehole whose typical depth is about 100m, and two three-component accelerometers are installed at the top and bottom of the borehole. To estimate the very shallow subsurface velocity between two sensors and its temporal change, we apply the coda wave interferometry (e.g., Schuster et al., 2004). Although, recently, Nakata and Snieder (2012) apply the deconvolution method to KiK-net data, in this study, we adopt cross-correlation method to obtain stable results. In the data processing, we select 1005 earthquakes that occurred between January 2004 and December 2011, and compute the cross-correlation function between surface and downhole records using five 2sec-long successive time windows starting from twice the S-wave travel time for each earthquake. Because the seismic coda wave, which appears after the body wave arrivals, are considered to be composed of multiply-scattered waves, the ensemble average of cross-correlation functions can be regarded as the Green function between two sensors. From the averaged cross-correlation functions, we estimated the near-surface velocity at frequency bands of 2-4, 4-8, 8-16Hz, and we also measure the temporal velocity change using time-stretching method.

Each obtained averaged cross-correlation function shows a clear wave packet traveling between borehole sensors, and its travel time is almost consistent with that of S-wave calculated from the borehole log data. During the period we analyze, two remarkable temporal variations are observed in the averaged cross-correlation functions: One is the co-/post-seismic change associated with large earth-quake, especially the 2011 off the Pacific coast of Tohoku earthquake occurred in March 2011, and another is seasonal/annual variation. It has been widely known that the strong motion due to large earthquakes causes rapid decrease and long-term recovery of shear wave velocity (e.g., Sawazaki et al., 2009). Our results also show the similar behavior with sudden velocity decrease of typically about 5-15% and gradual recovery which still continues at the end of 2011. In contrast, the observed seasonal/annual variation is about one order of magnitude smaller than the co-/post seismic change. Obtained near-surface velocity is smallest in the summer season, and the fraction of velocity change shows negative correlation to the precipitation, which is indicative of the effect of underground-level and corresponding change of effective pore-pressure at the shallow subsurface. These results demonstrate that the seismic interferometry is a useful tool to monitor shallow subsurface structure.

Acknowledgment: We used KiK-net data provided by the National Research Institute for Earth Science and Disaster Prevention.

Keywords: Seismic interferometry, Shallow subsurface structure, Temporal change

SSS27-P01 Room:Convention Hall Time:May 23 17:15-18:30

# Attenuation measurements of ultrasonic wave in partially frozen unconsolidated sands

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Ultrasonic wave transmission measurements were conducted in order to examine the influence of ice-brine coexisting system grown in unconsolidated porous material on ultrasonic P- and S-waves. We observed the variations of a transmitted wave, changing its temperature from 25 degree C to -15 degree C and quantitatively estimated attenuation for unconsolidated porous material during the freezing of brine in porous material by considering different distances between the source and receiver transducers. This paper is concerned with attenuation at ultrasonic frequencies of 350-600 kHz for P-waves and 150-250 kHz for S-waves. The waveform analyses for P-waves indicate that the attenuation curves reach their peak at a temperature of freezing point and gradually decrease with decreasing temperature, which is interpreted as the increase of the ice fraction or the increase of the effective bulk modulus of the system. The waveform analyses for S-waves indicate that the attenuation decreases with decreasing temperature, which is interpreted as the increase of the effective shear modulus of the system due to the increase of cementation of ice in the frozen sand. The laboratory experiments of the present study demonstrated that ultrasonic waves with such a frequency range are significantly affected by the existence of a solid-liquid coexistence system in the porous material. From liquid phase to around the freezing point, the presence of a partially frozen brine increases both velocity and attenuation. Attenuation estimation for P-wave is repeatable and stable while that for S-wave is not. However, the frequency content of S-wave shifts to higher with decreasing temperature. This implies that the attenuation decreases with decreasing temperature. In terms of a plausible mechanism for attenuation, we must consider the physical interactions between pore fluid, sands, and ice, that is, the pore microstructure and permeability in such system is important. Furthermore, several considerations on velocities using some theoretical models are also demonstrated.

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# Preliminary study to estimate elastic impedance in ground surface layer

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Dynamic response of structures during earthquakes depends on physical parameters in the ground due to the dynamic soil-structure interaction. The influence is complicated, but it is known that elastic impedance of ground layer associates with the radiation damping.

Normalized Energy Density (NED; Goto et al., 2011a) is a physical quantity related to wave propagation in multi-layered ground, and it becomes a constant value through each layer independent of how layer structure is. This characteristic enables us to directly estimate damping property of the layered ground when we observe NED in ground surface layer and NED in ground equivalent to the basement even we do not know concrete velocity structures of the layered ground (Goto et al., 2011b). NED is the function of elastic impedance in each layer. This means that it is necessary to measure the impedance in ground surface layer in order to calculate NED in ground surface layer.

In this study, we perform preliminary study by numerical experiment using finite difference method in order to consider a method of measuring elastic impedance in ground surface layer.

Hiroyuki Goto, Sumio Sawada and Toshiyuki Hirai: Conserved quantity of elastic waves in multi-layered media: 2D SH case -Normalized Energy Density-, Wave Motion, 48, pp.602-612, 2011.

Hiroyuki Goto, Sumio Sawada, Yuichi Kawamura, Toshiyuki Hirai and Takashi Akazawa: Definition of normalized energy density and its application to direct estimation of damping property, The 4th International IASPEI/IAEE Symposium on the Effects of Surface Geology on Seismic Motion, 2011.

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SSS27-P03 Room:Convention Hall Time:May 23 17:15-18:30

# Performance tuning of the Seism3D, the seismic wave propagation code, for large-scale parallel simulation using K comput

MAEDA, Takuto[1*], FURUMURA, Takashi[1], Shunsuke Inoue[2], Kazuo Minami[2]

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The "K computer" is the world's fastest super computer at present which has the maximum peak speed of more thatn 10 PFlops (Yonezawa et al., 2011). By using the huge computer resource of K, it is expected that there are massive improvements on numerical simulations such as seismic wave propagation or plate motion simulation in seismology. However, the K computer has more than 80,000 nodes (CPUs) that require us to highly tuned parallel computation. Additionally, the K's CPU has lower memory access speed relative to their flops. To overcome these technical difficulties, we measured the theoretical performance of our seismic wave propagation code "Seism3D" and did performance tunings from the aspects of the parallelization performance and single-CPU performance.

The Seism3D is a numerical simulation code based on the staggered-grid, finite difference method (FDM) explicit solver of the equation of motion of elastic medium (Furumura and Chen, 2005). We have improved the code in several aspects. First, we substituted the constitutive equation between stress and strain from the liner elastic solid to the generalized Zenner body to take broadband intrinsic attenuation into account. Second, the split-PML technique is used for an absorbing boundary condition at the model edges. This choice also enables us to simulate coseismic deformation at the sea floor and/or ground surface in addition to the seismic waves. The code can be extended naturally by incorporating the gravity and equilibrium between gravity and pressure field (Maeda and Furumura, 2011).

Simulation using the Seism3D requires large amount of memory access for referring inhomogeneous earth medium and wave/stress field at each time step. However, recent supercomputers including the K have relatively lower memory access speed compared to their CPU speed. Therefore, the ration between amount of the computation and amount of the memory access determine the maximum performance of the Seism3D as about 16 %.

For massive parallel simulations based on the MPI we also investigated the parallel balance between computational nodes. We found that the horizontal 2D partitioning, not 3D, is best for the computational performance. The single node assigns a rectangular parallelepiped shape having extremely long in the vertical direction. To obtain better performance, we exchanged computational loops among space so that the computation along z-direction is in the innermost loop. By this change, the continuous memory access is assured.

The data read from the memory are placed on L1- or L2- cache temporally. Because the access speed to cache is far faster than that to memory, the effective use on cache is mandatory for effective computation. In this point of view, we also tuned the cache access up (Minami et al., 2012). The K computer share the L2 cache among 8 CPU cores inside the nodes. By using this characteristic, we re-arranged the openMP-based parallelization inside a node so that at least the neighbor core can reuse the data on cache.

As a result, we achieved the 16 % of the maximum performance, which is almost the maximum speed of the Seism3D theoretically, on the K computer by the abovementioned tuning on benchmark codes. We will present the technical detail and some example of large-scale simulation by using the K computer.

Acknowledgements
This study is supported by the SPIRE field 3, MEXT. Part of this result is obtained by early access to the K computer at RIKEN Advanced Institute for Computational Science.

Keywords: Seismic wave propagation, numerical computation, numerical simulation, parallel computation, tuning

SSS27-P04 Room:Convention Hall Time:May 23 17:15-18:30

# Influence of Antarctic ice sheet on seismic waveform observations at intra-Antarctic region

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Recently, a lot of temporal broadband seismic stations had been installed on the intra-Antarctic region by the projects related to the International Polar Year (IPY) 2007-2008. Antarctica is known as a window toward the Earth's deep interior since it is the seismically quietest location on the Earth, it has wide extent enough to cover large epicentral distances needed to detect various seismic phases, and seismic waves observed at Antarctica cross regions within the Earth that previously have been sampled only poorly. We have been working to construct an accurate and efficient technique to model global seismic wave propagation. Our numerical scheme solves wave equations in spherical coordinates using the finite-difference method (FDM) based on the "2.5-D approach" which calculates 3-D seismic wavefields on a 2-D cross section of the Earth (e.g., Toyokuni et al., 2005, *GRL*).

This time, our method is applied to investigate influence of Antarctic ice sheet on observed seismograms obtained at intra-Antarctic region. We calculate synthetic seismograms for both a spherically symmetric Earth model PREM (Dziewonski & Anderson, 1981, *PEPI*) and a laterally heterogeneous model with a simplified ice sheet. In order to reduce equations and calculate synthetics up to higher frequency, only $SH$ wave is simulated by using a torque source assigned at a depth of 600 km. The ice sheet model has a constant thickness of 3 km and single values of the density (0.914 g/cm$^3$) and the $S$-wavespeed (2 km/s). In the presentation we will show several results obtained for source time functions with various pulse widths (4 s-30 s).

Keywords: seismology, synthetic seismogram, finite-difference method (FDM), global modeling, IPY2007-2008, Antarctica

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# Effect of complex surface topography on the distortion of the apparent S-wave radiation pattern

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**Introduction**

In the high frequency (f > 1 Hz), the observed maximum amplitude pattern don't show clear four-lobe pattern expected from a double-couple source [e.g. Liu and Helmberger, 1985; Takemura et al., 2009]. By analyzing a large number waveform data, Takemura et al. (2009) concluded that the main reason of such distortion is the seismic wave scattering due to small-scale velocity fluctuation in the medium. However, the resent studies revealed that the scattering due to irregular topography is also important for the propagation of high-frequency seismic waves. In order to clarify the effect of irregular surface topography on the distortion of the apparent S-wave radiation pattern, we conduct FDM simulations of seismic wave propagation in the model including topography.

**FDM Simulation including heterogeneous topography**

Our simulation model covers a zone 128 km by 128 km by 64 km, which has been descretized with grid size 0.1 km in horizontal direction and 0.05 km in vertical direction. In order to conduct such large scale simulations, we use a parallel staggered-grid FDM simulation technique. We assume the heterogeneous surface topography model provided by Geospatial Information Authority of Japan. In order to achieve precise simulation of high-frequency wave propagation, we employ the suitable boundary condition at the free surface [e.g. Okamoto and Takenaka, 2005; Maeda and Furumura, 2011].

We also assume the stochastic random heterogeneity characterized by exponential auto-correlation function with correlation distance a = 5km and rms value e = 0.05 and compare scattering properties of both heterogeneities. We assume a pure-strike slip at the center of model, depth h = 5 km, and so expected apparent S-wave radiation pattern at the free surface is a four-lobe shape

**Simulation results**

We conduct FDM simulation of seismic wave propagation in the three models, 1) uniform velocity structure model with surface topography, 2) flat surface model with stochastic random velocity fluctuation and 3) uniform back ground velocity model with both heterogeneities. We examine the maximum amplitude pattern of mean square envelopes for the sum of three components in frequency band of 2-4 Hz.

In the model 1, the amplitude pattern shows the four-lobe pattern maintains a four-lobe pattern, although the amplifications due to topography occur at the mountain regions. On the other hand, in the model 2, the effects of diffraction and scattering due to velocity fluctuation are accumulated during propagation and at larger distance (D> 30 km) the amplitude pattern is clearly collapsed from four-lobe pattern. In the model 3, the distortion become 11% stronger compared with the model 2 which is including velocity fluctuation alone.

Takemura et al. (2009) estimated the parameters of velocity fluctuation in the southwestern Japan by comparison of observation and simulation including velocity fluctuation alone. Therefore the estimation of velocity heterogeneities may be overestimated by the effect of irregular topography. We may be able to estimate the velocity fluctuation more precisely by considering the effects of irregular topography.

**Acknowledgement**

The computations were conducted on the Earth Simulator at the Japan Marine Science and Technology Center (JAMSTEC).

Keywords: Seismic wave propagation, Seismic wave scattering, Small-scale heterogeneity, topography, numerical simulation

SSS27-P06 Room:Convention Hall Time:May 23 17:15-18:30

# Lateral structure beneath the Izu-Nankai collision zone: Implication of a plate split in the subducting Philippine slab

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On July 5, 2011, an earthquake with a magnitude of 5.5 occurred off the Kii Peninsula in the northern Wakayama Prefecture in southwest Japan within the subducting PHS plate at depth of around 10 km. The earthquake caused strong shaking in the area near the epicenter. We analyzed the waveforms from this earthquake recorded at Hi-net and F-net stations in Japan. Such waveform analyses exhibit most of the earlier observations like dominance of low-frequency ($f < 0.25$Hz) onset and following high-frequency ($f > 2$Hz) energy with long coda due to the stochastic waveguide effect of the subducting plate, proposed earlier by Furumura and Kennett (2005). Interestingly, we observed a clear difference in wave propagation pattern between east and west of the epicenter. For example, the waveforms for eastern part show S-coda are depleted with high frequency energy as compared to the western part. The duration of S-coda varies alternatively between high and low from east to west through center of the epicenter. The central stations show loss of low-frequency precursor to P-waves and presence of converted phases in P-coda. Such complexities in the observed waveforms are difficult to explain due to the radiation pattern of P- and S-waves and/or by anomalous propagation of seismic waves in existing plate model, indicating sudden lateral change in the wave guiding properties of the subducting slab, such as caused by the splitting of the slab as proposed by Ide et al. (2010).

To explain the observations, we employ two-dimensional finite-difference method (FDM) simulations of complete high-frequency P-SV wave propagation taking thinning of the PHS slab into account. In the plate model we included stochastic random heterogeneities described by von Karmann distribution function with a longer correlation length of 10 km in horizontal direction and much shorter correlation length of 0.5 km in depth and standard deviation from background P- and S-wave velocities of 5% following the study of Furumura and Kennett (2005). We expect that the observed guided wave energy decouples from the waveguide where the slab is split. Low frequency energy leaks out of the slab in the low velocity mantle surrounding the slab. Taking into account the distribution of seismicity and focal mechanisms (Ide et al., 2010), and receiver function analyses (Shiomi et al., 2004) in the PHS plate, we expect a local velocity discontinuity or splitting of the plate at least to a depth of 30 km. Such a split in the PHS plate structure could also be manifested as non-volcanic tremor sources in the southwest Japan (Obara, 2002). The preliminary results, which suggest that the Philippine Sea slab is strongly split or partitioned beneath the Izu-western Nankai Trough in southwestern Japan, is the cause of the complicated waves from shallow inslab events. These effects need to be tested further with a 3-D FDM simulation employing high-performance computers with a variety of possible slab geometries. We finally discuss the implications of the new split plate model on the seismogenic potential of the area and the dynamics of the Nankai subduction in southwest Japan.

Keywords: philippine sea plate, wave propagation, numerical simulation, coda

SSS27-P07 Room:Convention Hall Time:May 23 17:15-18:30

# Ambient noise tomography in the eastern margin of the Japan Sea, NE Japan

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Seismic inteferometry has been used to estimate subsurface structure. Seismic inteferometry is based on the fact that cross-correlation function of random wavefields observed at a pair of stations contains Green's function between the two stations. Recently, seismic interferometry has been applied for ambient noise to estimate velocity structure, called ambient noise tomography. In this study, we applied this method for data of a dense seismic network in the region of the eastern margin of the Japan Sea. We estimated group velocity under the Sea of Japan and the western part of Tohoku region.

Date are vertical component of continuous record observed at 90 seismic station of Hi-net, JMA, Tohoku University, and temporary seismic stations installed for 'Multidisciplinary research project for high strain rate zone' promoted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. Time period of data is 10 months from January 2009 to October 2009.

First, we calculated daily cross-correlation function for each pair. We divided day-long data into 287 segments with a length of 10 minutes and with an overlap of 5 minutes and downsampled the data with a sampling with a sampling frequency of 20 Hz. Then we corrected instrument response. In order to avoid contamination of outliers such as natural earthquakes and packet deficits due to error of data transfer, we did not use the segments that include outliers. Determination of the earthquake was carried out automatically by using a root-mean-square value of the amplitude. After these procedures, we applied a fast Fourier transform for data segments and multiply the spectrum of the first segment with the complex conjugate of the second spectrum. The cross-spectra is normalized by spectral amplitude of both segments. We computed averaged cross-spectra over all segments. The daily cross-correlation function is obtained by applying invert Fast Fourier transform for the averaged cross-spectra. Finally, we stacked all available cross-correlations functions for each station-pair during 10 months.

We applied band-pass filter for the cross-correlation functions with three periodic bands 2-5 sec, 5-10 sec, and 10-20 sec. Line up of the cross-correlations in order of separation distance between the two stations shows clear seismic wave propagation with an apparent velocity of 3 km/s, which corresponds to the fundamental mode of Rayleigh wave. We estimated group velocity in the period of 5-10 sec, which the peaks emerge. Group velocity between two stations is calculated by dividing the separation distance by the peak time of envelope function. As a first step, we averaged group velocities between certain station and all the other stations and estimated average velocity for each station. The average velocity of each station is about 2.5-3.5 km/s.

Acknowledgment: This study is a part of 'Multidisciplinary research project for high strain rate zone' promoted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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# An application of seismic interferometry for DONET data

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From 0.05 to 0.2 Hz, background surface waves, known as microseisms, are dominant, and they mask seismic signals of earthquakes. The microseisms are excited by oceanic-swell activities at random. Recently using their random excitation properties, researchers have developed ambient noise tomography (e.g. Shapiro et al., 2005). The group velocity anomaly of Rayleigh wave is shown by cross-correlation functions between pairs of stations. The measurements by modern dense networks of broadband seismometers reveal fine tomographic images. There is an application of seismic interferometry for data of ocean bottom seismometers [e.g. Harmon et al, 2007, Yao at al., 2011], but investigations of their propagations are still ongoing in particular in high frequency (>0.1 Hz). In this study, we will clarify properties of wave propagation using a dense network on the sea floor. We analyzed vertical components of broad band seismometers (Guralp CMG3T) and pressure (absolute pressure gauge of Paroscientific inc.) from 2011/7/19-7/29 at 18 stations of Dense Ocean floor Network System for Earthquakes and Tsunamis (DONET), which consists of 5 sub arrays. We divided the records into segments of 409.6 s, and we discarded transients such as earthquakes and local noises. We calculated their normalized cross-spectra between all pair of stations. Corresponding cross-correlation functions (CCFs) of vertical components show clear Rayleigh wave propagation below 0.1 Hz. Because observed Rayleigh waves have sensitivity to accretionary wedge from 0.1 to 0.5 Hz, their waveforms are distorted with long coda parts. Above 0.5 Hz, Scholte waves, which are boundary waves between a fluid layer and a solid layer [e.g. Yao et al., 2011], become dominant. Their phase and group velocity is around 1.5 km/s. CCFs of pressure gauge also show similar features except for those at stations above thick accretionary wedge. At the stations from 0.2 to 0.5 Hz, fundamental Rayleigh waves are dominant in vertical components, whereas first overtones are dominant in pressure records. We estimated dispersion curves from CCFs, based on Aki's SPAC method. In regions of thick accretionary wedge, fundamental Rayleigh waves are not clear from 0.2 to 0.5 Hz in vertical components. Their phase velocity is about 500 m/s, whereas phase velocity in other regions is about 1000 m/s. Observed frequency is consistent with results of CCFs. In future studies, we will invert the phase velocity into local 1-D structure beneath each sub-array.

Keywords: seismic interferometry, surface wave

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# Seismic velocity changes due to the 2005 Miyagi-Oki Earthquake revealed from auto-correlation analysis of ambient noise

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We show temporal changes of auto-correlation functions (ACFs) calculated from ocean bottom records accompanied with the occurrence of a large interplate earthquake.

Seismic intererometry is one of techniques used to estimate the detailed properties of the Earth interior using a 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 the seismic interferimetry of ambient noise showed that ACFs and cross-correlation functions have temporal changes associated with strong motions due to local large earthquakes (e.g. Wegler et al., 2009).

The 14 ocean bottom seismometers (OBSs) were deployed off Miyagi before the 2005 M7.2 Miyagi-Oki Earthquake. All of the OBSs used in this study were a free-fall/pop-up type with a vertical component geophone. 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 the one-bit correlation technique. By taking ensemble average of ACFs among 24 hours, one-day ACFs were computed for several months including the Miyagi event at each station. The ACFs showed some common coherent phases throughout observing period. We assumed that computed the ACFs reflected subsurface structure just below the OBSs networks.

We investigated temporal variations of the ACFs during observed periods. Some distinguished coherent phases at lag times were delayed or changed after the 2005 Miyagi-Oki Earthquake. Furthermore, we investigated a dependence of a delay or change upon a lag time during the whole ACFs. We consequently found two factors for time-delay and change on ACFs due to the occurrence of the large earthquake. One is due to a decrease in seismic velocity around the stations owing to strong motions. The other is due to a local velocity change. If a local velocity change was observed by backscattered P waves, this change probably occurred at depths of ~30 km near the plate interface.

Keywords: Seismic interferometry, auto-correlation function, ocean-bottom seismometer, ambient noise, velocity change

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SSS27-P10 Room:Convention Hall Time:May 23 17:15-18:30

# Fractional velocity changes in Japan Islands related to the 2011 Tohoku-Oki Earthquake

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Using the Passive Image Interferometry (PII) method we investigated the temporal changes of the fractional velocity, dv/v, before and after the 2011 M9.0 Tohoku-Oki earthquake. Recently an increasing number of studies have documented abrupt dv/v changes after large earthquakes, swarms, and volcanic activities. We therefore considered that a huge earthquake, like the 2011 Tohoku event, could produce temporal changes of dv/v that can be found all over Japan. Our purpose is detecting the dv/v temporal change during the earthquake and investigating the relationship between such changes and other geophysical observations, in order to clarify the underlying physical mechanisms.

We applied the PII method to vertical-component continuous waveforms recorded during 2010 and 2011 by the Hi-net system (100 Hz sampling, with a natural frequency of 1 Hz). We divided the continuous record into segments of one hour length, removed the mean and trend and applied 1-3 Hz band-pass filtering and one-bit normalization. Auto-Correlation Functions (ACFs) were calculated for the one-hour segments and stacked for time intervals of one week to obtain good stability. We employed the mean ACFs in 2010 as a reference ACF to calculate phase shifts for daily ACFs. Since the fractional velocity, dv/v, can be estimated by using the phase shift between the reference ACF and the daily ACFs, we could monitor the dv/v before and after the 2011 Tohoku earthquake. We quantified the temporal changes of dv/v by calculating the difference between the mean dv/v for the month before and the one after the Tohoku earthquake, using a bootstrap resampling method. To investigate the cause of the temporal changes, we compare them with the volumetric strain, calculated using source models of the huge earthquake, or Peak Ground Acceleration (PGA), recorded by KiK-net, whose seismometer is installed at the same borehole of Hi-net.

From the comparison of the time periods before and after the Tohoku earthquake, we have obtained a velocity decrease in the Tohoku, Kanto and eastern Chubu regions, as well as in the western part of the Hokkaido district. In contrast, a velocity increase was obtained in eastern Hokkaido, western Chubu, Kinki and Chugoku district, although it was slightly weak. Comparing these dv/v changes with the volumetric strain, calculated using source models of the large earthquake, we have found that the dv/v clearly decreases more than 10-6 in strain. The dv/v also changes in the area where moderate and large PGAs (more than 10 gal) were observed.

Our results suggest that the strain changes in the crust, caused by the huge earthquake, correlate with the dv/v temporal variations. Especially the relationship between the dv/v decrease and the positive volumetric strain appears to be clear. This result was also obtained during the eastern Izu Peninsula swarms. For the area of the dv/v increase, the volumetric strain was less than 10-7 and shows an unstable pattern of compression/extension: compression in the eastern Hokkaido and extension in the west of Chubu district. Furthermore, it is complicated to infer the dv/v increase from PGA data of large earthquakes.

Keywords: seismic interferometry, The 2011 Tohoku-Oki Earthquake, temporal changes

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# Temporal seismic velocity changes associated with the 2011 Tohoku Earthquake from repeating earthquakes analyses

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Recent studies using seismic wave interferometry for ambient noise report temporal changes of about a few percentages in seismic velocity of the structure associated with occurrences of large earthquakes and volcanic activities. These studies generally analyze surface waves with a period of about 1-10 s, hence the structures changing seismic velocity are considered to be quite shallow, about a few hundred meters to 1 km. In the present study, seismic velocity changes associated with the 2011 off Pacific ocean of Tohoku earthquake (M9) are reported based on analyses of similar earthquakes occurring before and after the earthquake.

From the hypocenter data base of JMA, we select earthquakes with magnitude of about 4 and find earthquake groups in which hypocenters of several earthquakes are located within a distance of about a few kilometers. Then, calculating the cross-correlation coefficients for the waveforms for about 30 s from the P-waves, we select similar earthquakes. By applying cross-spectrum method to direct P- and S-waves for a pair of the selected similar earthquakes, travel time differences of P- and S-waves for the two earthquakes are calculated The results obtained from the analyses of 8 pairs of similar earthquakes occurring at depth of 40 - 60 km show following characteristics. Travel time differences of P-waves are quite small, almost less than 0.01 s. On the other hand, significant changes are observed in the travel time differences of S-waves: Tohoku region where the M9 faults are closely located show travel time increases of about 0.01-0.06 s while Kanto, Chubu and Hokkaido regions do not show significant velocity changes. Travel time differences of S-waves detected in the east-west component are slightly larger than those in the north-south direction. Travel time differences are not observed both for P- and S-waves for the pairs of similar earthquakes occurring before M9 earthquakes. Therefore, the travel time increases of S-waves observed around Tohoku regions are caused by the occurrence of the M9 earthquake.

Seismic velocity decreases, that correspond to travel time increases, are often discussed with reduction of the rigidity of the shallow structure that are damaged by strong motions. The travel time increases observed in the present study may be explained by this mechanism. In such cases, the stations characterized by low S-wave velocity at shallow parts are expected to observe large travel time differences. But, the spatial distribution of shallow S-wave velocity measured in boreholes is not well correlated with the distributions of travel time differences. This inconsistency may suggest that some deeper regions decrease the S-wave velocity.

Keywords: Temporal seismic velocity change, The 2011 off the Pacific Coast of Tohoku Earthquake, crustal structure, repeating earthquake

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# Detecting temporal changes in shallow subsurface structures by auto correlation analysis of coda waves

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Seismic interferometry using ambient noise records has been successfully used to detect temporal changes in a subsurface velocity structure. So far, velocity changes have been found to be associated with large earthquakes and volcanic eruptions [e.g. Sens-Schoenfelder and Wegler (2006); Brenguier et al. (2008)]. Though coda waves, which may contain more body waves than ambient noises, will be better to detect reflected waves from interfaces at depths, we can not help waiting earthquakes. But at regions with high seismicity, it may be possible to monitor subsurface structures. Though seismic interferometry using downhole array records is very efficient to detect temporal changes in shallow subsurface [e.g. Sawazaki et al., (2009)], it requires borehole records. In this study we propose to use auto-correlation function of coda waves recorded at surface receivers to detect subsurface velocity structures. And we apply this method to the 2011 Tohoku-Oki earthquake, with which velocity changes have been reported to be associated by Wu and Peng (2011) and Nakata and Snieder (2011). So the purpose of this study is to validate the auto-correlation analysis of coda waves for monitoring.

We use KiK-net stations in the Pacific side of Northern Honshu (from Aomori to Chiba). At each station, records from earthquakes of M smaller than 7.0 which occurred at depths of 20-60km off Pacific region in 2010 and 2011. Two horizontal component acceleration records at the surface are used. In the frequency range of 1-20Hz, normalized auto correlation function of the record is calculated for a 10.24 s?long coda waves starting from the 1.5 times the direct S-wave travel time. We repeat such calculations 20 times by sliding time windows by 1 s. Normalized auto correlation functions are stacked with respect to different time windows. Aligning the stacked normalized auto correlation functions along time, we try to find changes in arrival times of phases in the auto correlation functions. Focusing on shallow depths, we deal with phases in lag times of less than 1s. According to the results, temporal variations are found at some stations. Especially, clear phase delays are found at stations along the coast in Iwate and Ibaraki. And this change is associated with the mainshock. Amounts of phase delays are in the order of 10% on average with the maximum of 30%. This method seems to have an accuracy of about a few percent, which is much larger than methods using earthquake doublets [e.g. Poupinet et al. (1984)]. So this method might be applicable to detect larger changes. In spite of these disadvantages, this method is still attractive because it can be applied to records on the surface without boreholes.

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Keywords: seismic interferometry, auto correlation function, coda wave