Estimation of S-wave scattering coefficient in the mantle from envelope characteristics before and after the ScS arrival

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[1] Examining seismogram envelopes of regional earthquakes in Central Asia with focal depths deeper than 150 km in 1s–20s periods for a wide lapse time range up to 2000s, we found an offset in each coda envelope before and after the ScS arrival at 10s and 15s periods. The ScS wave has its own tail, that is, scattered waves of ScS waves sometimes dominate over the original coda waves composed of scattered S waves and scattered surface waves. For 1s, 2s and 4s periods, such an offset is not clear. However, there is a change of coda decay gradient associated with the ScS arrival. In a layered velocity and attenuation structure according to the PREM, scattering process of S-waves can be simulated by using the Monte Carlo method based on the radiative transfer theory for isotropic scattering process. Comparing numerical simulation for a two-layered scattering model with observed envelopes, we estimated the total scattering coefficients as 1.129 × 10^{-3} km^{-1} and 6.230 × 10^{-4} km^{-1} at 4s, and 4.510 × 10^{-4} km^{-1} and 2.710 × 10^{-4} km^{-1} at 10s, for the lithosphere and upper mantle and for the lower mantle, respectively. In the lower mantle, scattering loss is dominant in the total attenuation of S waves.


1. Introduction

[2] The excitation level of coda waves and the temporal decay gradient of coda amplitudes characterize the scattering strength and attenuation of the real earth medium. There have been a lot of measurements of coda attenuation $Q_{C}^{-1}$ and total scattering coefficients over the world [e.g., Sato and Fehler, 1998]; however, most of coda measurements reported were done for lapse times shorter than a few hundred seconds and for periods shorter than 1s. That is, most of these values characterize the heterogeneity of the lithosphere. There were some exceptions: Biswas and Aki [1984] $Q_{C}^{-1}$ reported in Alaska for periods from 1s to 10s, and Sato and Nohechi [2001] reported the excitation of Rayleigh-wave coda of periods for 100s–200s for longer lapse times. Rautian and Khalturin [1978] reported that coda envelopes of local earthquakes have a few lapse time segments characterized by different attenuation parameters. Assuming the decrease of $g_{0}$ with depth, Gusev [1995] theoretically predicted the decrease of $Q_{C}^{-1}$ with increasing lapse time.

[3] Since the most prominent velocity contrast deep in the earth is the CMB, reflected phase ScS clearly appears in long period seismograms. Reflected phases associated with mantle discontinuities also appear on seismograms; however, there have been no reports on the envelope characteristics before and after these arrivals.

[4] Having interests in the mantle heterogeneity, we examine the coda decay characteristics of regional deep focus earthquakes recorded at an IRIS station in Central Asia. We measure the decay of coda envelopes in several period bands from 1s to 20s for lapse times as long as 2000s. This lapse time range includes ScS and ScS$_{2}$ arrivals. For events deeper than 150 km in depth, we estimate especially the total scattering coefficient $g_{0}$ for 4s and 10s period bands using the direct simulation Monte Carlo (DSMC) method [Yoshimoto, 2000].

2. Observation Data

[5] Broadband velocity seismograms of regional earthquakes registered by the AAK station of the IRIS network in Central Asia were used for the analysis. From the data collected during the period from 1992 to 2001, 15 NS-component seismograms were chosen for this study. Their magnitudes range from 5.3 to 6.5, epicentral distances are less than 1000 km, and focal depths are deeper than 150 km up to 250 km (Figure 1).

[6] Second-order Butterworth band-pass filters having center periods of 1s, 2s, 4s, 10s, 15s and 20s are applied to data. Smoothing the square of band-pass filtered trace, we compute mean square (MS) envelopes. As an example, in Figure 2, gray traces exhibit the logarithmic plot of band-pass filtered MS envelopes. In order to correct the source-size differences, we plot these traces normalizing the average coda level at lapse time ranging from 650s to 750s as marked by a bold solid bar at the bottom. Vertical
dashed lines indicate theoretically calculated $S$ and $ScS$ arrivals based on the IASP91 model. The black trace is a stacked trace for each period band. As seen in these plots, at 1s, 2s and 4s periods, the decay gradient is smooth irrespective of the $ScS$ arrival and there is little difference in envelope levels before and after the $ScS$ arrival. At 10s, 15s and 20s periods, however, the $ScS$ phase is clear, the envelope decay gradients are different before and after the $ScS$ arrival, and there is an offset of the envelope level around the $ScS$ arrival. That is, the $ScS$ wave has its own tail. We examined envelopes of shallow earthquakes; however, this characteristic is more prominent for MS envelopes of earthquakes with focuses deeper than 150 km. Thus, we confine our attention to deep focus events only in this study. Some phases arriving after the $ScS$ arrival have been explained as reflections from the mantle discontinuities, the CMB and the earth’s surface [Revenaugh and Jordan, 1989]. Similar offset and tail appearing in coda envelopes of local earthquakes in Kanto, Japan were reported by Obara and Sato [1988], and they interpreted the offset by the reflection on the surface of the subducting Pacific plate. Considering the similarity of the stacked envelopes with those observed for coda waves of local earthquakes, we propose to explain the envelope characteristics by the scattering of $S$-waves due to distributed heterogeneities in the mantle and the reflection at the CMB.

3. Numerical Simulation

[7] We use the direct simulation Monte Carlo (DSMC) method [Yoshimoto, 2000] for the simulation of $S$ wave envelopes in scattering media based on the radiative transfer theory with a complex spatial variation of velocity. For the simulation, we considered only $S$ wave and assumed isotropic scattering consistent with an acoustic model with point scatterers. We use the velocity structure of $S$-wave having a positive gradient with depth as illustrated in Figure 3, which is a slight modification of the original PREM model [Dziewonski and Anderson, 1981]. According to the PREM, total attenuation profile chosen mostly from body wave studies can be approximated by a two-plane-layered model where the boundary is 670 km in depth. We neglected the narrow low $Q$ zone at 80–220 km in depth; total attenuation $Q_o$ of the upper layer (Layer 1) and the lower layer (Layer 2) are 143 and 312, respectively. The scattering power per unit volume is given by $g_0$ value in each layer for each period. The total attenuation $Q_o$ works as a strong constraint for the range of variation of $g_0$ value.
We found changes in coda envelope decay gradient before and after the ScS arrivals in the MS envelopes for the period bands from 4s to 20s. In Figure 2, we could not see any offset and the envelopes have just small coda decay period bands from 4s to 20s. In Figure 3, we could not see before and after the ScS period bands. The vertical offset, however, appears after the grid search analysis to seek gradient change around the ScS period bands. The change of coda decay gradient, except only change once around the ScS arrivals, is more than 5 dB for 10s–20s. We could not find such anomaly, however, in smaller period bands. The change of coda decay gradient associated with the ScS arrival becomes smaller as the period becomes shorter.

Aki and Chouet [1975] and Rautian and Khalturin [1978] concluded that coda envelopes after 1000s in lapse time are mostly excited by scattered waves in later coda. It might mean that coda waves of periods longer than 1s are too strong in observed data, however, our model is not able to simulate surface wave scattering. For 1s and 2s period bands, the synthetic envelopes based on a two-layered scattering model are not able to explain simultaneously the strong ScS peak observed and the smooth decay of envelopes.

The residual takes a minimum value at \( g_0 = 1.129 \times 10^{-3} \) (1.032 \times 10^{-3} \sim 1.548 \times 10^{-3} \) for ±20% in error) km\(^{-1}\) for Layer 1 and \( g_0 = 6.230 \times 10^{-4} \) (4.984 \times 10^{-4} \sim 6.930 \times 10^{-4} \) for ±20% in error) km\(^{-1}\) for Layer 2 at 4s. g\(_0\) = 4.510 \times 10^{-4} (4.059 \times 10^{-4} \sim 5.412 \times 10^{-4} \text{ for ±10% in error}) km\(^{-1}\) and \( g_0 = 2.710 \times 10^{-4} (2.439 \times 10^{-4} \sim 2.770 \times 10^{-4} \text{ for ±10% in error}) km\(^{-1}\) at 10s for Layer 1 and Layer 2, respectively. In Figure 4, we show the stacked observation data by gray curves and the best-fit synthetic envelopes by black curves for the period bands 4s and 10s. It exhibits good coincidence between them except lapse time around 250s for 10s period. The discrepancy before 250s could be explained by the influence of surface waves. We can find a small offset with a small coda decay gradient for 4s and a clear offset with a big change of coda decay gradient for 10s after the ScS arrival in the simulation. For period bands, 15s and 20s, the influence of the surface waves is too strong in observed data, however, our model is for S-wave scattering and is not able to simulate surface wave scattering. For 1s and 2s period bands, the synthetic envelopes based on a two-layered scattering model are not able to explain simultaneously the strong ScS peak observed and the smooth decay of envelopes.

5. Discussion

Scattered S-waves or scattered surface waves are dominant in coda before the ScS arrival; however, scattered waves of ScS waves sometimes dominate over those scattered waves in later coda. It might mean that coda envelopes after 1000s in lapse time are mostly excited by ScS waves. There is a bend of envelope decay and a level change around the ScS arrival, which is more than 5 dB for 10s–20s. We could not find such anomaly, however, in smaller period bands. The change of coda decay gradient associated with the ScS arrival becomes smaller as the period becomes shorter.

Aki and Chouet [1975] and Rautian and Khalturin [1978] reported that coda envelopes show a systematic step-like change in decay rate with lapse time; however, we could not find such a systematic decay rate change, except only change once around the ScS arrival in the simulation. For 1s and 2s period bands, the synthetic envelopes based on a two-layered scattering model are not able to explain simultaneously the strong ScS peak observed and the smooth decay of envelopes.
The total scattering coefficient of $S$-waves in the lithosphere has been widely measured over the world for short periods and that of Rayleigh waves was measured for long periods. In Figure 5 we plot our results with those measurements. We believe that the scattering coefficients estimated in this study are quite reliable especially to understand the medium heterogeneity of the lower mantle.

From a preliminary survey of seismograms of regional deep focus earthquakes over the world [Lee et al., 2002], we found similar characteristics in $S$ wave envelopes before and after the $ScS$ arrival and the change in coda level varies from station to station. We note a contribution of surface wave scattering in addition to $S$-wave scattering especially before the $ScS$ arrival. It suggests that it is necessary for us to discriminate the contribution of surface wave scattering and reflection and conversions at the mantle discontinuities in order to measure the spatial variation of mantle heterogeneity.

6. Conclusion

Examining seismogram envelopes of regional earthquakes in Central Asia in periods from 1s to 20s for a wide lapse time range up to 2000s, we found that the change of coda decay gradient becomes smaller as the period becomes shorter after the $ScS$ arrival. We also found that envelopes have clear offsets around the $ScS$ arrivals especially at 10s and 15s periods for earthquakes with focuses deeper than 150 km. That is, the $ScS$ phase has its own decaying tail. These observations suggest that scattered waves of the $ScS$ waves sometimes dominate over scattered $S$ waves and scattered surface waves. As a result of grid search by using the DSMC method for synthesizing $S$ wave envelopes, we estimated the scattering coefficients using total attenuation of the PREM as a restriction. For the two-layered scattering model, the resultant total scattering coefficients are $1.032 \times 10^{-3} \sim 1.548 \times 10^{-3}$ km$^{-1}$ and $4.984 \times 10^{-4} \sim 6.930 \times 10^{-4}$ km$^{-1}$ at 4s, and $4.059 \times 10^{-4} \sim 5.412 \times 10^{-4}$ km$^{-1}$ and $2.439 \times 10^{-4} \sim 2.770 \times 10^{-4}$ km$^{-1}$ at 10s, for Layer 1 and Layer 2, respectively. The scattering mainly controls the seismic attenuation when the seismic waves pass through the lower mantle. Thus we can imagine that much stronger scattering than intrinsic attenuation might cause the offset.

Figure 5. Resultant total scattering coefficients of $S$-waves in the mantle from the analysis of $ScS$ records observed in Central Asia are marked by open and solid diamonds for Layer 1 and Layer 2, respectively. Total scattering coefficients of $S$-waves for short periods in the lithosphere (Modified after Figure 3.10 of Sato and Fehler [1998]) and those of Rayleigh waves for the lithosphere and the uppermost mantle [Sato and Nishino, 2002] are also plotted.
behavior and coda decay gradient change after the ScS arrival for 4s and 10s period bands.

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