Analysis of the lapse time dependence of the distribution scattered waves by using 3D FD simulations

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Short-period seismograms which consist of scattered waves due to small-scale heterogeneities show complex waveforms. The early part of the envelope from the onset to the early coda through the peak consists of narrow-angle scattered waves and can be modeled by the Markov approximation which is the multiple forward-scattering approximation [Sato, 1989]. Conversely, the contribution of wide-angle scattered waves becomes large at the late coda part. Consequently, the energy flux at the late coda becomes isotropic. To quantitatively analyze the distribution of scattered waves, we applied the FK technique to the simulated waveforms [Emoto, 2017 SSJ]. However, the time resolution of the FK analysis was not enough and the physical meanings of the distribution of the peak FK value were not clear. In this study, we calculate the ensemble of the energy flux by using the finite difference (FD) simulation, which corresponds to the specific intensity or the angular spectrum. Therefore, we can compare it with those of theoretical methods such as the radiative transfer theory and the Markov approximation.

We investigate the angular spectra for the random media of the following four cases of the correlation distance (*a*) and the RMS fluctuation (ε): (*a*, ε) = 1: (1 km, 0.05), 2: (10 km, 0.05), 3: (1 km, 0.1), 4: (5 km, 0.01). The medium of the FD simulation is a cube. The grid separation is 80 m and the total number of grids is 3840^3. The source is located at the center of the medium and the stations are set at the propagation distances of 25, 50, 75 and 100 km. To calculate the gradient of the wavefield to calculate the energy flux, we set additional receivers at neighboring grids. At each travel distance, we set 20 receivers on the concentric sphere. In total, we conduct the FD simulations for 12 difference realizations of random media, therefore, we analyze 20 x 12 = 240 energy fluxes. Calculating the distribution of these energy fluxes, we obtain the angular spectrum. The maximum calculated lapse time is 45 s. We also calculate the angular spectra by using the Monte Carlo (MC) simulation based on the radiative transfer equation and the Markov approximation and compare them with that derived by the FD simulation. The Born approximation used in the MC simulation is not appropriate for the case 2, therefore we use the newly improved method proposed by Sato & Emoto (2018, JpGU) for this case.

The angular spectrum shows a sharp peak at the direction from the source to the receiver just after the onset. The distribution becomes smooth with increasing lapse time. The angular spectrum derived by MC simulation well fit that derived by the FD simulation. The distribution derived by the Markov approximation can model that by the FD simulation at the early lapse time for the cases 2 and 4. However, it overestimates the energy of large angle scattered waves for the cases 1 and 3. The cases 1 and 3 are out of the range of the applicable condition of the Markov approximation. Because the Markov approximation is based on the multiple-forward scattering theory, it cannot consider the scattered waves which have the incident angles over 90 degrees. The correlation of the transverse plane perpendicular to the propagation direction becomes too sharp for the cases 1 and 3. Therefore, the angular spectrum the Fourier transformed of the correlation has the amplitude over 90 degrees. In that case, the angular spectrum cannot be defined in the Markov approximation. Our results show that the Markov approximation can model the scattered waves whose incident angles are less than 30 degrees.

The distribution of the case 4 has the sharpest peak at the early lapse time and that of the case 2 is the

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second sharpest. The difference of shapes of the distributions becomes small with the increase of the lapse time. For example, the difference almost disappears several seconds after the onset at the propagation distance of 50 km. After that lapse time, the distributions of all cases become flat in a similar way. As pointed by Emoto (2017 SSJ), we confirm that the speed that the distribution converges into the isotropic flux is almost independent of the parameters of random media.

Keywords: Scattered Waves, Random Media, Finite Difference Simulation, Radiative Transfer Theory, Markov Approximation

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