Geological Sciences Research (GEOL490.3), 2017/2018, Term 1

Modeling seismic coda from local earthquakes

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Problem

This research will focus on modeling the shapes of “seismic coda” envelopes observed in the records of most local (recorded at 0 to 100 km distances from the epicenter) earthquakes. The coda is recorded at a single station and represents a decaying train of ”random” oscillations containing no recognizable arrivals (P-, S-, or surface wave). The purpose of coda models consists in predicting the shapes of the envelopes of the amplitudes of these oscillations, which allows inferring the physical properties of the lithosphere from the observations of seismic codas.

The general explanation of the coda consists in its being mostly composed of S waves scattered within the crust and uppermost mantle (Aki, 1969, 1980). Several scattering models have been developed in order to explain coda observations quantitatively. These models generally describe the physical properties of the crust by two parameters: 1) the average scattering strength and 2) the energy absorption due to intrinsic or scattering attenuation. The most broadly used model was proposed by Aki and Chouet (1975) model explains the coda by singly-backscattered waves in a medium with a uniform distribution of point scatterers. In these models, single scattering occurs at large distances and at points located uniformly around the source-receiver region (Figure 1). Therefore coda waves arrive at the receiver from all directions and at all times

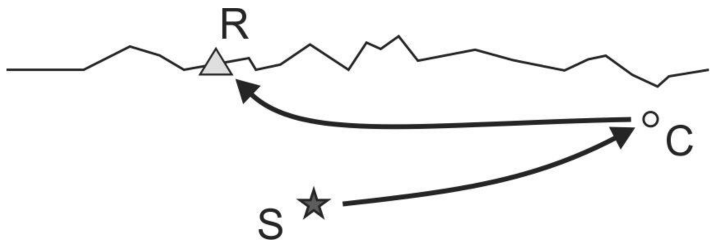

Figure 1. Schematic model of coda recording. The earthquake source (S) is located relatively close to the receiver station (R). The recorded wavefield consists of waves scattered at multiple points C located at large distances around S and R. In Aki and Chouet's (1975) and other models used today, the rays SC and CR are viewed as straight and the corresponding waveforms are spherical.

after the direct S wave. Aki and Chouet (1975) also introduced the commonly-measured parameter called "coda *Q*", or Q_c. This parameter gives the time- and frequency-dependent coda amplitude envelope as:

$$A(f,t) = \frac{A_0}{t} e^{-\pi ft/Q_c} . \quad (1)$$

However, the physical significance of parameter Q_c remains unclear. Q_c is often found to be frequency and time-dependent and decomposed into an "intrinsic" and "scattering" *Q*-factors (Wennerberg, 1993).

Several authors proposed models of multiple scattering, in which the scattering occurs multiple times. Multiple scattering leads to somewhat different dependences of coda amplitudes on time (Wennerberg, 1993). However, the Aki and Chouet's (1975) and *all* models used for today's coda data analysis contain one common major drawback, which consists in assuming straight rays between the scattering points and uniformly-distributed scattering intensity within the whole crust. Considering the generally layered crustal structure, these assumptions are highly unrealistic. Morozov (2008, 2010) argued that inaccurately assuming a uniform crustal structure leads to spurious increase of Q_c (eq. (1)) with frequency, which is commonly found in coda measurements.

The goal of the present project will be to investigate the changes in eq. (1) occurring when more realistic models for geometric spreading and distributions of crustal scatterers are chosen in single-scattering coda models. In addition, you will also investigate the effects of non-zero source-receiver separation on eq. (1).

Method

Let us consider the attenuation-free case ($Q^{-1} = 0$ for the material of the crust). Let us also consider horizontally-layered crust, so that the direct-wave (SC in Figure 1) and scattered-wave (CR in Figure 1) amplitudes only depend on the separations between points S, C and C, R, respectively. The single-scattered energy density at point R is then given by an integral over the entire volume surrounding points S and R:

$$A(t) = \int_V d^3\mathbf{r}_C G_f\left(\mathbf{r}_C - \mathbf{r}_S\right) s\left(\mathbf{r}_C\right) G_s\left(\mathbf{r}_R - \mathbf{r}_C\right), \quad (2)$$

where $s(\mathbf{r})$ is the scattering intensity, and $G_f(\mathbf{d})$ and $G_s(\mathbf{d})$ are geometric spreading factors for direct ("forward"-traveling) and scattered waves, respectively, at distance vectors $\mathbf{d}$ from the origin.

You will need to evaluate the integral in eq. (2) numerically by assuming several types of dependences $G_f(\mathbf{d})$, $G_s(\mathbf{d})$, and $s(\mathbf{r})$, and several values of source-receiver distances. For each of the $G_f(\mathbf{d})$, $G_s(\mathbf{d})$, power-law dependences need to be tried:

$$G(\mathbf{r}) = t^{-2\nu}, \quad (3)$$

where $\nu = 1$ for body waves (as in Aki and Chouet's (1975) model), $\nu = ½$ for surface waves. Other useful values representing diving crustal waves would be, for example, $\nu = 1.1$, 1.3, 1.6, and 2.0. The forward-traveling and scattered waves can be different; for example, body waves can be scattered and return to the receiver as surface waves.

For the depth distribution of scatterers $s(\mathbf{d})$, let us test: 1) a constant throughout the whole lower half-space (as in Aki and Chouet's (1975) model), 2) scattering at the free surface only, 3) scattering at the Moho (at 40-km depth), and 4) uniform scattering within the upper crust (8-km layer believed to be brittle, seismogenic, and therefore heterogeneous).

The resulting coda-envelope $A(t)$ dependences can be compared and examined in two ways. First, similar to Wenerberg (1993), plot the logarithm of the modeled amplitude corrected for the $1/t$ dependence in Aki and Chouet's (1975) model:

$$\delta(t) = \ln\left[A(t)\cdot t\right] + c\,, \tag{4}$$

where the constant c can be selected arbitrarily. Second, by plotting $\ln\left[A(t)\right]$ versus $\ln t$ approximate dependences of the form

$$A(t) \approx \frac{1}{t^{\alpha}}\,, \tag{5}$$

can be fit. You will need to estimate, report, and compare the values of α for the different test cases.

Expected results

A research paper and presentation summarizing the results of this project will be prepared. Coda and other seismic data can be interpreted without the Aki and Chouet's (1975) assumptions (Jhajhria et al., 2017), and findings of this project will directly contribute to such interpretations. The results of this research could contribute to several papers on coda data analysis that are currently in preparation.

Work plan

(This work plan can be used as an outline of your expected report).

Numerical modeling will be conducted by using Matlab on computers in Rm. 111 or elsewhere. Octave software can also replace Matlab very well.

1) Visit the library, study the recommended and other literature, and compile information for the report. Look for answers to the following questions:

    a. What are the assumptions of the Aki and Chouet's (1975)? What do they mean in the sense of: shapes of the rays and wavefronts? Velocity structure of the crust and uppermost mantle? distribution of scatterers? frequency dependence of scattering amplitudes? source-receiver distance?

    b. Look for empirical geometric-spreading models for direct waves different from $G(t) \propto 1/t$.

    c. For the assumptions of the Aki and Chouet's (1975) model, show that with $Q_c^{-1} = 0$, the integral in eq. (2) indeed gives eq. (1).

2) Implement eq. (2) for numerical integration in 3-D. Use Cartesian, cylindrical, or spherical coordinates as preferred. Use typical seismic velocity values for the crust and upper mantle, coda observation times. Select the integration grid size equal about one dominant wavelength for S waves within the crust. Make sure the integration volume contains all possible scattering points at the longest coda time.

3) Perform modeling for several combinations of exponents ν (eq. (3)), distributions of scatterers, and source-receiver distances. Evaluate the effects by using eqs. (4) and (5) .

4) Discuss the results:

    a. Are the values of α always positive?

    b. Do they differ substantially between the different cases? Do they vary with coda lag times?

    c. Jhajhria et al. (2017) measured $\alpha \approx 1.7$. To what values of ν and forms of $s(\mathbf{r})$ could this value correspond?

Evaluation

Recommended examining committee

1) Sam Butler
2) Jim Merriam
3) Igor Morozov

Grading:

Paper:	50%
Oral presentation:	30%
Computer scripts, plots, and test examples in electronic formats:	20%

References and recommended reading

(required papers are highlighted in **bold**)

Aki, K. (1969), Analysis of the seismic coda of local earthquakes as scattered waves, Bull. Seism. Soc. Am. 74, 615–631.

Aki, K. (1980). Attenuation of shear-waves in the lithosphere for frequencies from 0.05 to 25 Hz, Phys. Earth Planet. Interiors 21, 50–60.

Aki K., and Chouet, B. (1975), Origin of coda waves: source, attenuation, and scattering effects, J. Geophys. Res. 80, 3322–3342.

Jhajhria, A., Morozov, I. B., and Teotia, S. S. (2017), Frequency-dependent coda amplitude decays in the region of Himalaya. Bull. Seism. Soc. Am, doi: 10.1785/0120170032.

Wennerberg, L. (1993), Multiple-scattering interpretations of coda-*Q* measurements, Bull. Seism. Soc. Am., 83, 279-290.

Morozov, I. B. (2008) Geometrical attenuation, frequency dependence of *Q*, and the absorption band problem, Geophys J Int 175: 239–252

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Morozov I. B., and Baharvand Ahmadi A. (2015), Taxonomy of *Q*, Geophysics 80 (1): T41–T49, doi: 10.1190/geo2013-0446.1

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