Extended-source waveform inversion of volcanic long-period/very-long-period seismic signals

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Long-period (LP) events with typical oscillation periods of 0.2-2 s, and very-long-period (VLP) events with typical durations in the range 2-100 s, are frequently observed in active volcanoes. These signals are related to acoustic vibrations and/or volumetric changes of a fluid-filled resonator, in which the fluid has a hydrothermal or magmatic origin. Here, we propose a method to investigate the size and oscillation characteristics of the source of LP/VLP signals based on waveform inversion carried out for an extended source. The hypocenter, geometry, and orientation of the source are first estimated based on waveform inversion assuming a point source. An extended source is then realized by a set of point sources distributed on a grid surrounding the hypocenter in accordance with the known source geometry and orientation. The mechanism of each point source is fixed by the mechanism obtained from waveform inversion for the initial single point source, and the source-time functions for all point sources are estimated simultaneously by waveform inversion carried out in the frequency domain. As the number of free parameters and attendant noise increase with the number of sources, we apply a smoothing constraint to suppress short-scale noisy fluctuations of moment release between adjacent sources. The smoothing parameter we select is that which minimizes the Akaike Bayesian Information Criterion (ABIC).

We demonstrate the capability of our method through a series of numerical tests. In our first test, we use synthesized waveforms that mimic radiations from an oscillating crack. A set of 3x3 point sources spaced 50 m apart is arranged on a vertical plane centered at a depth of 300 m. A decaying monochromatic oscillation with frequency of 2 Hz and Q=25, is used as source-time function for each point source. A crack oscillating in the mode with wavelength 2W/3, in which W is the horizontal extent of the crack, is then synthesized by multiplying amplitudes by a factor -1/2 the source-time functions of all the point sources distributed symmetrically off the main axis of the modeled crack. The ground response to the crack is obtained by summing the synthetics obtained for each point source, assuming a source embedded in a homogeneous half space. Trial models of waveform inversion include sets of 3x3 point sources spaced 25, 50, 75, and 100 m apart and 5x5 sources spaced 25 and 50 m apart, centered at a depth of 300 m. Waveform inversions for a finite source are carried out using 14 receivers distributed within 1 km from the source. The lowest ABIC is given by a set of 3x3 sources spaced 50 m apart, which is identical to the input, and demonstrate that the source-time functions are well reconstructed.

In our second test, we use synthetic waveforms generated by the acoustic resonance of a fluid-filled crack model. We assume a vertical crack with horizontal extent of 140 m and vertical extent of 280 m, with its top edge located 200 m below the surface, and synthesize the waveforms from the 2W/3 mode and L and 2L/5 modes, where L is the vertical length of the crack. Trial reconstruction models include sets of 3x3, 5x5, 3x5, and 5x3 point sources spaced 25, 50, 75, 100, 125 m apart, centered at a depth of 350 m. The lowest values of ABIC are obtained for a set of 3x3 sources spaced 100 m apart, rather than the input crack with vertical elongation. This limited spatial resolution is the result of the lesser number of free parameters covering the source area in the inversion model compared to the original model. However, once the approximate area of the source is known, we can examine the source elongation and the detailed crack oscillation signatures using a higher spatial density of sources. With this improved spatial resolution, a vertically-elongated crack yields the second lowest ABIC and its oscillation signatures are successfully reconstructed.