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Point spread functions for earthquake source imaging

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Recently, various methods such as back-projection method (e.g. Ishii et al., 2005), time-reversal (TR) method (e.g. Larmat et al. 2006), and hybrid back-projection (HBP) method (Yagi et al., 2012) have been proposed and applied for earthquake source studies in addition to kinematic waveform inversions (e.g. Hartzell and Heaton, 1983) . In addition, theoretical relationships among the methods have also been clarified (e.g. Kawakatsu and Montagner, 2008, Fukahata et al., 2013). In this study, we introduce the notion of the point spread function (PSF) into earthquake source imaging, and show that the PSF clarifies the meaning of the earthquake source inversions. Under ideal circumstances in which receivers continuously surround the source, the PSF can be interpreted with seismic interferometry.

Kinematic waveform inversion methods are now standard for earthquake source studies. The observation equations (or forward modeling equations) are based on the representation theorem. According to Claerbout (2001), imaging is defined to be the mathematical process of multiplying adjoint Green's functions with both sides of the observation equation. Fukahata et al. (2013) pointed out that the process is very close to the one used in the HBP method. The source image may be blurred and degraded due to uneven distributions and insufficient number of stations. The degree of blurring and degradation can be expressed by the PSF which is often used in optics. The PSF for the source imaging can be expressed by stacked cross correlations of Green's functions between two source points with respect to receivers on a surrounding surface. If distributions of sources and receivers are discretized, the observation equation can be formulated in matrix form. Source inversion is found to remove the effect of the PSF, but other source imaging methods suffer from the PSF.

Ideal circumstances are considered here to better clarify the meaning of the PSF. It is assumed that stations are continuously distributed so as to surround the source points. For this case, we use source-receiver reciprocity of Green's functions. Then, we can consider the following reciprocal configuration in which sources are surrounding two stations. The point spread function is expressed as the stacked cross correlations of waveforms between the two receivers with respect to the surrounding sources. This configuration is exactly the same as ones in seismic interferometry and therefore we can interpret the PSF based on seismic interferometry. For single-force sources, the PSF is found to be the imaginary part of the Green's function. This fact was already pointed out in terms of TR method (e.g. Fink, 2006). For moment-tensor sources, the PSF is shown to be the imaginary part of the spatial derivative of Green's function with respect to each coordinate of the two receivers. This is a novel finding of this study. It is also suggested that the source image is the integrated version of the true source process when the interpretation based on seismic interferometry strictly holds.

In summary, kinematic source inversion methods can remove the effect of the PSF, but other source imaging methods suffer from blurring and degradation by the PSF. As a result, careful weighting of data is necessary for the source imaging methods. For ideal cases in which receivers surround the sources, the PSF can be interpreted with seismic interferometry with the help of the source-receiver reciprocity of Green's functions. This study will contribute to better understanding of the meaning of source inversion methods.

Keywords: Earthquake source imaging, Point spread functions, Seismic interferometry