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Past, Present, and Future of Seismic Interferometry

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SUMMARY

I give an overview of the long history in of seismic interferometry, starting with Einstein's work in 1906 on Brownian motion, through developments in physics in the 1950's to the surge in seismic interferometry in 2000's. I indicate the possibilities and limitations of the method, and pose a number of challenges.
A brief history of interferometry

The history of the extraction of the system response goes back to Einstein (1906) who showed that the response of a system to a random excitation, in his case Brownian motion of a large molecule suspended in air, is equivalent to knowing the response of a system to an excitation (the Green’s function of the kicked molecule in the air). This principle was in the 1950’s shown to be applicable to general quantum mechanical systems (e.g. Green and Callen, 1951). In thermodynamics this principle is known as the fluctuation response theorem (Le Bellac et al., 2004) which states that for a system in thermal equilibrium that:

$$\frac{\partial \langle A_i \rangle}{\partial \lambda_j} = \langle (A_i - \langle A_i \rangle)(A_j - \langle A_j \rangle) \rangle$$

where $\langle \ldots \rangle$ denotes the expectation value. In this expression $A_i$ is a thermodynamic state variable, such as pressure, and $\lambda_j$ a control parameter, such as volume. The left hand side gives the response to the system to a control parameter $\lambda_j$, i.e. the Green’s function. The right hand side gives the cross-correlation of fluctuations.

It was Lobkis and Weaver (2001) who formulated the fluctuation response theorem using normal modes. This was a language that resonated with seismologists, which has led to a revolution in global and exploration seismology. Key players in this development were Michel Campillo, Gerry Schuster, and Kees Wapenaar. One of the spectacular successes of seismic interferometry was the retrieval of surface waves. Oceanic noise is most prominently generated for periods between 5 and 10 seconds. Surface waves at these periods sample the crust. With seismic interferometry one can obtain the surface waves propagating between every pair of seismometers, which brings an unprecedented resolution to surface wave seismology (Shapiro et al, 2005; Sabra et al., 2005). For these reasons seismic interferometry has revolutionized crustal seismology.

Figure 1 The wave field obtained Lin et al. 2009, from cross-correlating ocean-generated noise recorded at the station marked with the star with the noise recorded at all other stations of US-Array (triangles) for lag times of 100 s (left panel) and 200 s (right panel).

The principle is illustrated in Figure 1 which shows the cross correlation of oceanic noise of one master station, indicated with a star, with all other stations (triangles) if US-Array. The master station clearly acts as a source from which a circular wave front radiates through the array. In reality there is no such source, for this reason one speaks of a virtual source.
Current status

Seismic interferometry has been extremely successful for extracting surface waves. It was shown that both Rayleigh waves and Love waves can be retrieved (Behm et al., 2014). The Achilles heel for extracting the Earth response from noise is the distribution of noise sources. According to theory, noise sources with equal source strength must be present on a closed surface surrounding the receivers. This condition is in practice not satisfied and as a result it has proven difficult to extract high-fidelity body waves from recorded noise measurements (Forghani and Snieder, 2010). In exploration seismology, this problem has been circumvented by placing receivers in boreholes and using controlled sources at the Earth’s surface (Bakulin and Calvert, 2006; Schuster, 2009), but in general body waves are not forgiving for inadequacies in the distribution of sources for the field fluctuations.

Challenges and opportunities

Extracting the Earth response from field fluctuations faces the following challenges and opportunities.

(1) The extraction of body waves. Although recent work has shown spectacular examples of body waves propagating through Earth’s core (Lin et al., 2013), we don’t properly understand under which conditions we can extract clear body waves from field fluctuations. (2) There may be an opportunity for low-quality cheap controlled source to provide the noise bath that is needed for the extraction of body waves. This would be particularly relevant for monitoring purposes. (3) The extraction of the system response from noise has had spectacular successes in seismology. Extending these principles to other geophysical fields (e.g. pore pressure, the DC electric field, and potential fields) may open up new opportunities to probe and monitor the subsurface (Snieder et al., 2010).

References