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Passive multi-channel analysis of surface waves with cross-correlations and beamforming. Application to a sea dike

M. Le Feuvre *, A. Joubert, D. Leparoux, P. Côte

LUNAM University, IFSTTAR, F-44344 Bouguenais, France

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ABSTRACT

We introduce the use of cross-correlations in the passive multi-channel analysis of surface waves (MASW), and report an improvement in the determination of subsurface shear velocities from ambient seismic noise. Velocities are measured from phase-shifts that are also related to the source location. Consequently, the accuracy with which velocities can be inferred depends on the ability of the array to locate noise sources. The computation of cross-correlations for each receiver pair allows increasing the effective spatial sampling of the array. For this reason, we show that beamforming is more efficient with cross-correlated signals. Consequently, MASW performed with cross-correlations produces a dispersion diagram where aliasing is reduced and signal-to-noise ratio increased. The proposed method is validated with synthetic records. It is then applied on passive recordings obtained on top of a sea dike at high tide, where sea waves were acting as continuous seismic sources. Surface wave velocities that favorably compare with hammer shot measurements are inferred.

1. Introduction

In recent years, seismic methods based on the analysis of surface waves have been actively tested in different contexts of subsurface issues, involving different scales of investigated depth and resolution. For example, Satyam and Rao (2008), Socco et al. (2008), Casto et al. (2009), Ryden and Mooney (2009), Socco et al. (2010), Leparoux et al. (2012) and Samyn et al. (2013) presented various studies, where all the mentioned approaches involve data generated by active seismic sources, such as hammer shots (see Socco and Strobbia, 2004 for a tutorial). However, in specific applied geophysical topics, such as monitoring approaches, it is useful to escape from the necessity of active sources. Passive seismic methods, that rely on natural seismic noise, allow for the layout of long-term in situ experiments dedicated to the characterization of the mechanical evolution of structures with time. For example, sea dike monitoring is now identified as a major issue for natural hazard assessment due to climate disorder, with the need to follow the response of the structure to tidal cycles, seasonal variations, storms and aging (in France, a strong financing plan has been voted by the government after the catastrophic flooding events caused by the Xynthia storm, in 2010). Furthermore, while active seismic surveys relies on isolated energetic sources, passive seismic methods benefit from a variety of noise sources that averages over time. The achieved resolution is potentially higher than for active measurements, provided that the directionality of the seismic noise is properly accounted for (e.g. Aki, 1957; Park et al., 2007; Gouedard et al., 2008; Halliday et al., 2008). Because surface waves constitute the main part of the seismic energy recorded in shallow measurements, interferometric methods have proven to be well suited for dispersion analysis (e.g. Wathelet et al., 2004; Asten, 2006; Renalier et al., 2010; Bitri et al., 2011). At the civil engineering scale, where stiffness is a key parameter, the inference of shear velocities from dispersion analysis with active sources is now common practice. Passive measurements, however, may be complicated by 1) the lack of natural sources in the relevant frequency band, and 2) the geometry of the field, that does not always allow to deploy 2D arrays capable of removing ambiguities about the directionality of noise (e.g. Park and Miller, 2008).

At local scale, dispersion curves from active surveys are usually determined by measuring phase-shifts on multi-channel records (multichannel analysis of surface waves, abbreviated as "MASW"). If the investigated medium does not show strong lateral variations, this approach allows 1) to cope with the strong subsurface attenuation by maximizing the signal-to-noise ratio, 2) to properly isolate the different propagation modes, and 3) to investigate the medium in a large range of depths, since various wavelengths are resolved, depending on the distance between receivers. Among this family of multi-channel methods (for a review, see Rost and Thomas, 2002) the approach of Park et al. (1999) is commonly regarded as providing both a better resolution and investigation depth than the frequency–wavenumber method (Capon and Bolt, 1973). Since it relies on phase-shifts measurements, the active scheme of Park et al. (1999) has been extended to the passive case, by introducing a scanning process along potential azimuthal directions of noise (Park et al., 2004; Park and Miller, submitted for publication). The method has been tested on tidal and anthropogenic noise, such as seismic

* Corresponding author.
E-mail address: mathieu.le-feuvre@ifsttar.fr (M. Le Feuvre).

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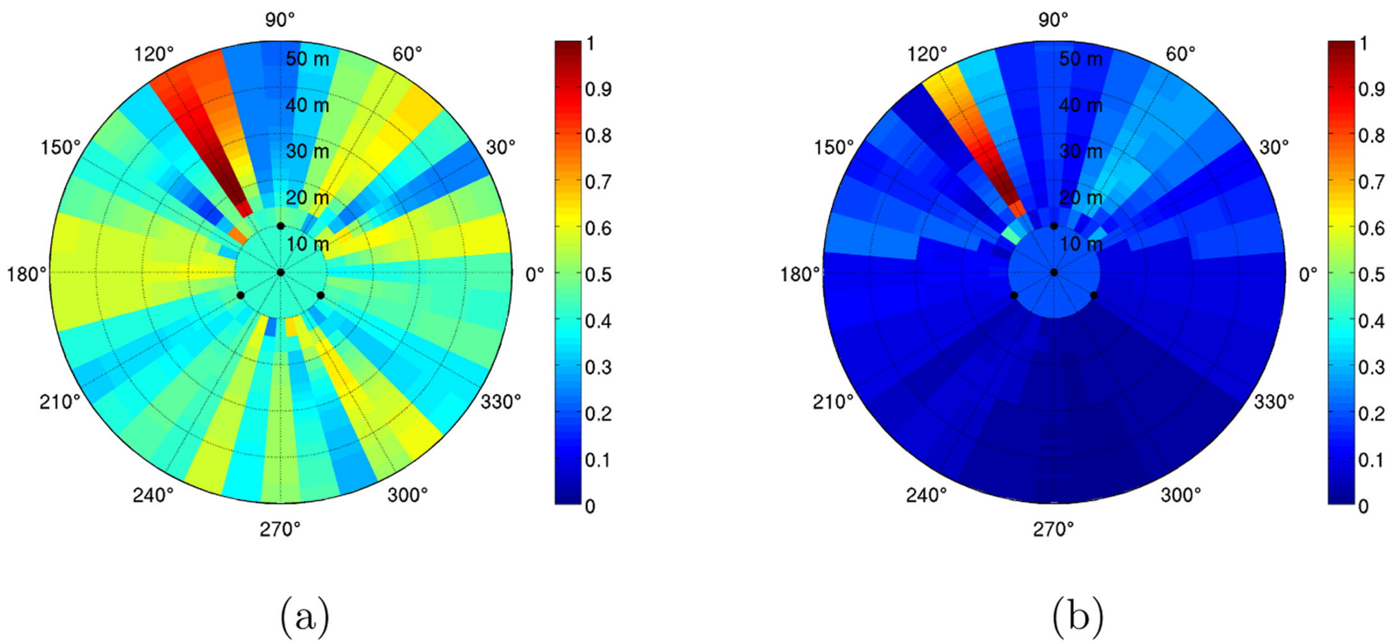

Fig. 1. Normalized beamforming output for (a) original signals and (b) cross-correlated signals. The source is located at polar coordinates ($r = 20$ m, $\theta = 120$ °). Receivers are depicted with black dots. Cross-correlations improve the source localization power of the array.

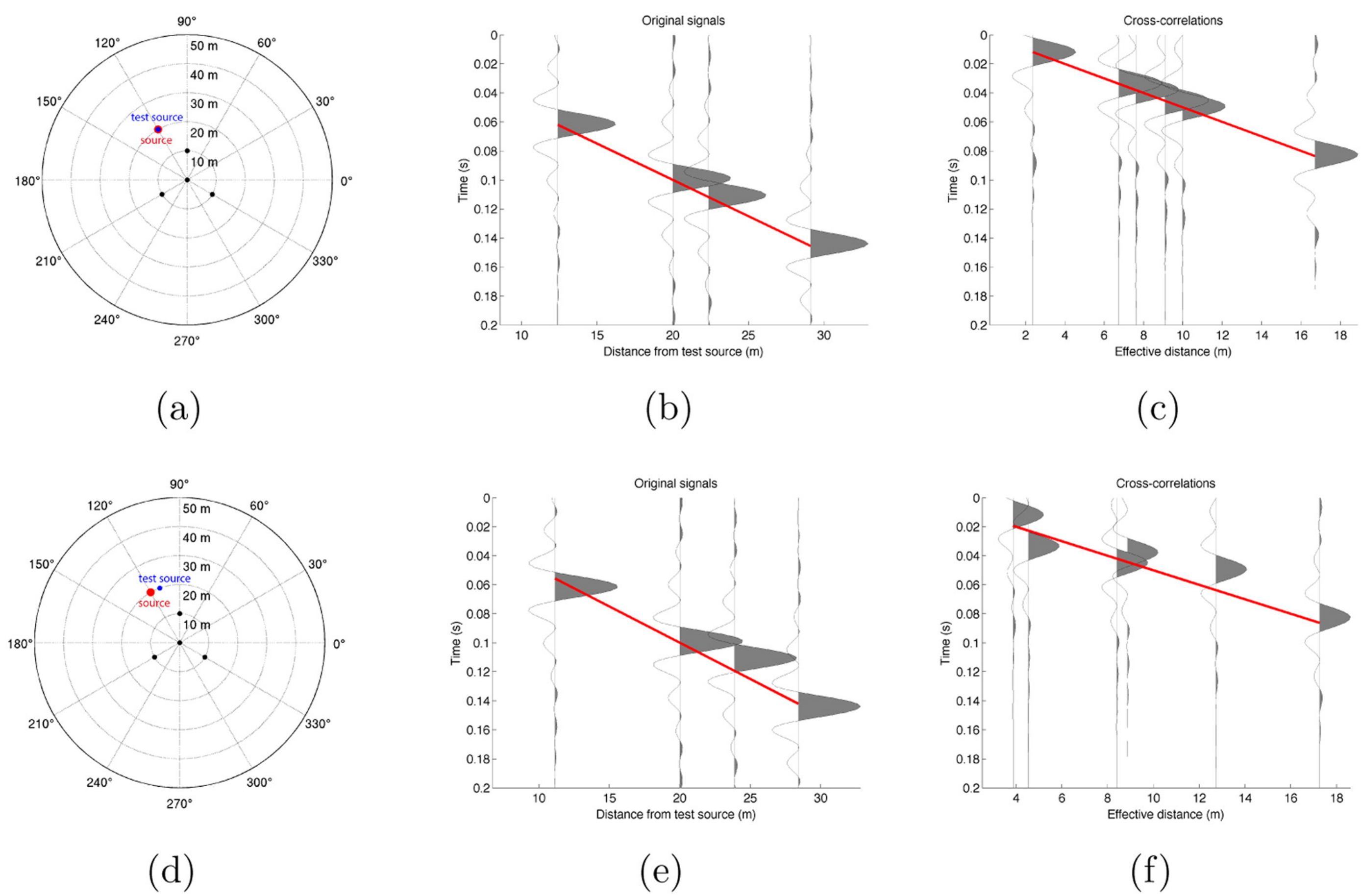

Fig. 2. Details about the calculation of Fig. 1. Top: (a) test source (in blue) located at the actual source point (in red). (b) Original signals plotted as a function of the distance from the test source. (c) Cross-correlated signals plotted as a function of the effective distance (see text for details). Bottom: (d) test source located 10° away from the actual source point. (e) Original signals plotted as a function of the distance from the test source. (f) Cross-correlated signals plotted as a function of the effective distance. Cross-correlations enhance the deviation from the linear velocity slope (red line) for a bad location of source. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)