Journal of Applied Geophysics 117 (2015) 126–135

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

# A new passive seismic method based on seismic interferometry and multichannel analysis of surface waves

Feng Cheng [a], Jianghai Xia [a,b,*], Yixian Xu [b], Zongbo Xu [a], Yudi Pan [a]

[a] Subsurface Imaging and Sensing Laboratory, Institute of Geophysics and Geomatics, The China University of Geosciences, 388 Rumo Rd., Wuhan, Hubei 430074, China
[b] Hubei Subsurface Multi-scale Imaging Key Laboratory, Institute of Geophysics and Geomatics, The China University of Geosciences, 388 Rumo Rd., Wuhan, Hubei 430074, China

ARTICLE INFO

*Article history:*
Received 4 December 2014
Received in revised form 6 April 2015
Accepted 7 April 2015
Available online 11 April 2015

*Keywords:*
Passive seismic method
Seismic interferometry
MASW
Virtual source method

ABSTRACT

We proposed a new passive seismic method (PSM) based on seismic interferometry and multichannel analysis of surface waves (MASW) to meet the demand for increasing investigation depth by acquiring surface-wave data at a low-frequency range ($1 \text{ Hz} \leq f \leq 10 \text{ Hz}$). We utilize seismic interferometry to sort common virtual source gathers (CVSGs) from ambient noise and analyze obtained CVSGs to construct 2D shear-wave velocity (Vs) map using the MASW. Standard ambient noise processing procedures were applied to the computation of cross-correlations. To enhance signal to noise ratio (SNR) of the empirical Green's functions, a new weighted stacking method was implemented. In addition, we proposed a bidirectional shot mode based on the virtual source method to sort CVSGs repeatedly. The PSM was applied to two field data examples. For the test along Han River levee, the results of PSM were compared with the improved roadside passive MASW and spatial autocorrelation method (SPAC). For test in the Western Junggar Basin, PSM was applied to a 70 km long linear survey array with a prominent directional urban noise source and a 60 km-long Vs profile with 1.5 km in depth was mapped. Further, a comparison about the dispersion measurements was made between PSM and frequency–time analysis (FTAN) technique to assess the accuracy of PSM. These examples and comparisons demonstrated that this new method is efficient, flexible, and capable to study near-surface velocity structures based on seismic ambient noise.

## 1. Introduction

"Noise" turns into useful signals in retrieving Rayleigh waves from ambient noise using seismic interferometry. The retrieved surface waves and reflected waves can be used to infer geological properties of the shallow and deeper subsurface structure. Seismic interferometry or ambient noise cross-correlation has now routinely been used to extract travel-time information between two stations and applied to study interior earth structure (Brenguier et al., 2007; Moschetti et al., 2010; Lin et al., 2013). While retrieving surface waves is still one of the major applications (e.g., Shapiro et al., 2005; Yao et al., 2006; Lin et al., 2008), several recent studies have also shown the possibilities of extracting body waves using seismic interferometry (Poli et al., 2012; Lin et al., 2013; Nishida, 2013). Surface waves in different periods can be used to investigate the Earth's structure at different depths. Generally, in most of these studies, waves at frequencies well below 1 Hz were used to image the crust and the upper-mantle structure (Yang et al., 2008; Stehly et al., 2009; Nishida et al., 2009). Recent studies show that the seismic interferometry can also be applied to frequencies higher than 1 Hz (Picozzi et al., 2008; Halliday et al., 2008). Those kinds of applications focus on the knowledge of the subsurface structure from tens to hundreds of meters, and as a result, the interest is located in the short period range.

Multichannel analysis of surface waves (MASW) has been utilized for imaging and characterizing near-surface structure (Xia et al., 2009). High-frequency ($\geq 2$ Hz) Rayleigh-wave data acquired with a multichannel recording system have been utilized to determine shear (S)-wave velocities in near-surface geophysics since the early 1980s. A comprehensive review of MASW can be found in Xia et al. (2009). MASW is increasingly popular among the academic and engineering communities as a non-destructive, non-invasive, inexpensive and accurate seismic imaging method applicable to a variety of near-surface geological and geophysical problems.

Using active-source imaging methods, increasing the depth of investigation by a few tens of meters requires order-of-magnitude increases in active-source energy to extend the low-frequency end of the dispersion curve by a few Hertz (e.g. to include a 2–7 Hz frequency range). Rendering deep-sounding MASW with an active source is impractical and uneconomical (Park et al., 2007). To make the MASW practicable, Park et al. (2007, 2008) proposed a passive MASW survey, which can be divided into two different types based on field logistics and type of

---

[*] Corresponding author at: Subsurface Imaging and Sensing Laboratory, Institute of Geophysics and Geomatics, The China University of Geosciences, 388 Rumo Rd., Wuhan, Hubei 430074, China.
*E-mail addresses:* jianghai_xia@yahoo.com, jxia@cug.edu.cn (J. Xia).

http://dx.doi.org/10.1016/j.jappgeo.2015.04.005
0926-9851/

$V_S$ profiles (1D or 2D) obtained, passive remote and passive roadside MASW surveys. This type of application originated almost half a century ago in Japan under the name of Microtremor Survey Method (MSM) (Tokimatsu et al., 1992). Spatial Autocorrelation (SPAC) (Aki, 1957; Roberts and Asten, 2004) and f–k methods (Capon, 1969; Asten and Henstridge, 1984) were commonly used to process passive surface waves for dispersion analysis.

In this paper, we propose a new passive seismic method, which we call PSM, based on seismic interferometry and MASW. We describe the processing scheme for PSM using ambient noise acquired with a multichannel recording system. Specifically, we show that higher SNR surface wave signals can be retrieved from ambient noise cross-correlation (Bensen et al., 2007) by our weighted stacking method than those acquired by traditional stacking methods. Using a new bidirectional shot mode, we show that it is possible to sort common virtual source gathers (CVSGs) more efficiently than sorting based on the traditional roll-along mode of measurement (Xia et al., 2004a,b). Finally, the PSM is implemented in two field data tests with different scales and the dispersion measurements are compared with the improved roadside passive MASW, SPAC (Chάvez-García et al., 2006) and FTAN (Lin et al., 2008), respectively.

## 2. Data processing scheme

The PSM method comprises seismic interferometry and MASW. The data processing component of the method contains two parts: 1) retrieving Rayleigh-wave signals from noise, which is called seismic noise interferometry, and 2) determining S-wave velocity structure from CVSGs using MASW. We closely follow the procedure described by Bensen et al. (2007) to obtain traditional ambient noise cross-correlations using continuous noise data acquired with a multichannel recording system. The specific objective frequency band (≥1 Hz) in the local scale, however, is prominently higher than that of global scale (7–150 s), and the observation time is usually limited to several hours or days and hardly ever can be permitted to months or more. Both the limitations mentioned previously restrict the quality of retrieved Rayleigh waves. To address this problem, we improve the traditional stacking method with an SNR weighting algorithm to improve seismic noise cross-correlation results, which will be described in the following section. Subsequently, MASW is applied to mapping a final 2D $V_S$ profile. It is worth mentioning that we design and set a bidirectional shot mode to sort CVSGs, which is more effective than the traditional roll-along mode of MASW. In this paper we subdivide the two parts of the PSM method into four phases. A schematic representation of the method data processing flow is shown in Fig. 1.

### 2.1. Weighted stacking method

To improve the quality of stacking results, namely the empirical Green function, we present a new stacking technique, called SNR-weighted stacking. In traditional stacking, all cross-correlations are stacked together. For urban areas with high levels of culture noise

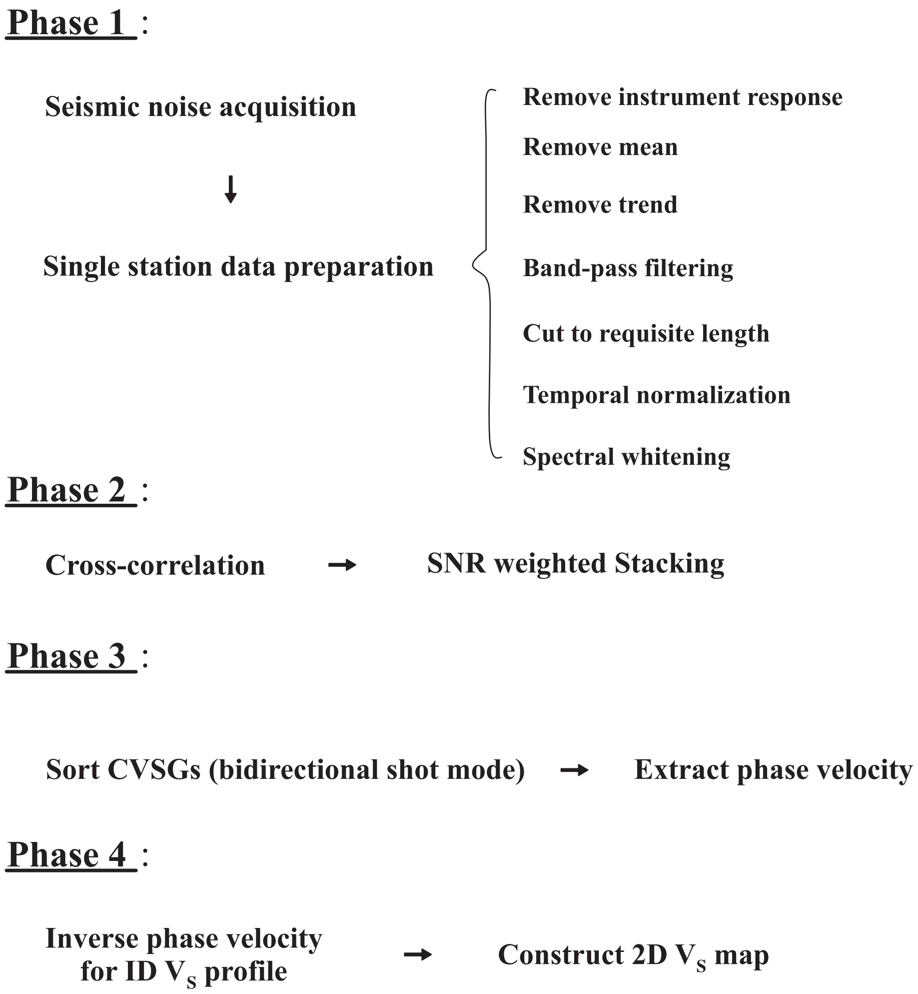

**Fig. 1.** Schematic representation for data processing scheme of the PSM. Phase 1 shows the steps involved in preparing single-station data prior to cross-correlation. Phase 2 outlines the cross-correlation procedure and stacking. It deserves to be mentioned that we add a quality control operation to improve the SNR of the obtained signals from stacking. Phase 3 includes bidirectional shot mode CVSG sorting and dispersion measurement of each virtual source gather. Phase 4 is inversion and 2D $V_S$ profile mapping.