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Towards Super-resolution Surface Wave Tomography Using Interferometry

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Summary

A Rayleigh surface wave tomography is proposed with an optimal coverage approach based on the creation of virtual raypaths by interferometry. Array based conventional surface wave picking methods often provide inhomogeneous or sparse coverage for high-resolution surface wave tomography. The delivered inversion results can suffer from acquisition pattern imprints or poor lateral resolution. We propose to create new optimally chosen virtual raypaths that better condition the information. The kinematics of Rayleigh wave's Green functions are then analyzed by a direct inversion of the surface wave phase interference pattern. The concept is proved on synthetics and illustrated on a 3D real data example.

Introduction

Rayleigh waves are increasingly attracting interest as they provide complementary information to body waves for various applications, such as near-surface velocity model building or geotechnical assessment (Al Mesaabi et al., 2017). Ideally we would use 3D elastic full waveform inversion but, given the huge amount of traces to process (>billion), it remains a very time consuming method. Hence, we propose to follow the first steps of a convenient workflow, such as Duret et al. (2016), to process and invert Rayleigh waves. The objective is to solve the first bottleneck that conditions the rest of the shear wave velocity (Vs) estimation workflow, that of Rayleigh wave velocity picking.

In land acquisition data are often acquired with a cross-spread geometry, as it provides the best wide azimuth 3D symmetrical sampling for body wave processing. For surface waves however, this geometry usually results in an under-sampling of the near surface structure. Velocity information is mainly aggregated along source and receiver lines, leading to the appearance of acquisition imprints when we want to access high-resolution information. Limitations are linked to the usual array based (or multi-channel) approaches for Rayleigh wave velocity picking, such as multi-channel analysis of surface waves (MASW) (Park et al., 1999, Zhen et al., 2014) or multi-offset phase analysis (MOPA) (Strobbia et al., 2006). Heterogeneities smaller than the array length are conventionally difficult to correctly estimate (Mi et al., 2017) due to various parameters, including the assumption of a homogeneous media within the array extension.

To break free from the usual source-receiver geometry paradigm, we use interferometry techniques to access a better conditioned virtual raypath network that will regularize and finely sample the media. To avoid averaging velocities by an array and estimating fine velocities for each short offset pair, we perform a least square inversion of the phase interference pattern of Rayleigh waves for each virtual couple (Chmiel, 2016) to estimate its dispersion curves before surface wave tomography.

We give a theoretical description of the approach along with a proof of concept on synthetics. It is then illustrated on a small 3D test area for a land survey acquired by Petroleum Development of Oman (PDO).

Choice of optimal raypath for densification and virtual ray velocity estimation

Conventional surface wave dispersion curve measurements (like MASW or MOPA) are generally based on the use of an array of receivers (Figure 1-a) that averages the surface wave velocity within the array extension. To increase the tomographic resolution, we want to access a direct measurement of the velocity dispersion between each location (Figure 1-b) which can be made possible by interferometry properties described below. Another limitation of conventional velocity picking is the associated ray coverage. The hit count density and azimuth diversity of short offset rays are biased by using source-receiver pairs acquired along receiver and source lines (Figure 1-c). Interferometry helps to solve this issue by giving access to pairs of sources and pairs of receivers thanks to virtual ray computation (Figure 1-d). Hence, an optimal pattern which provides a homogeneous coverage is accessible. We focus on the application of this concept to cross-spread geometry acquisition, but it can be extended to any type of geometry showing coverage issues, or a need for higher resolution.

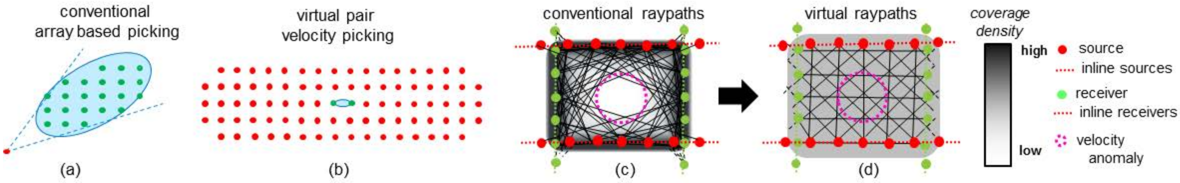

Figure 1 *Averaging velocity area extension (blue disk) for conventional array based picking (a) and individual virtual pair by interferometry (b). In (c) and (d), schematic consequences on information coverage for one 'cell' of a cross-spread. Meaningful rays are shown for conventionally acquired seismic (with offset diversity for array based picking) (c); or for virtual source-source and receiver-receiver raypaths (d). Small velocity anomalies are more regularly sampled. Only three azimuth sectors of virtual rays are represented, but a denser network of virtual rays can be created.*

Firstly, the Green’s kinematics function is estimated by interferometry for each virtual pair, despite approximations related to the limited coverage with surface cross-spread recordings (Halliday and Curtis, 2008). The created virtual rays show very little offset diversity and array based picking approaches cannot be used. Hence, as a second step, with the example of a virtual receiver-receiver couple (Figure 2-a), we do not sum cross-correlations located at each source location to retrieve a trace, but we individually analyze the phase correlation values between the two receivers for each source (Figure 2-b). At a given frequency, this observed phase interference pattern characterizes the inter-receiver velocity. It can be modelled and inverted by a least-square approach (Chmiel, 2016), providing an original method to pick Rayleigh dispersive velocities for all frequencies (Figure 2-c). Velocity is no longer averaged over an array extension but estimated between each individual pair of receivers (or sources), which provides a higher resolution.

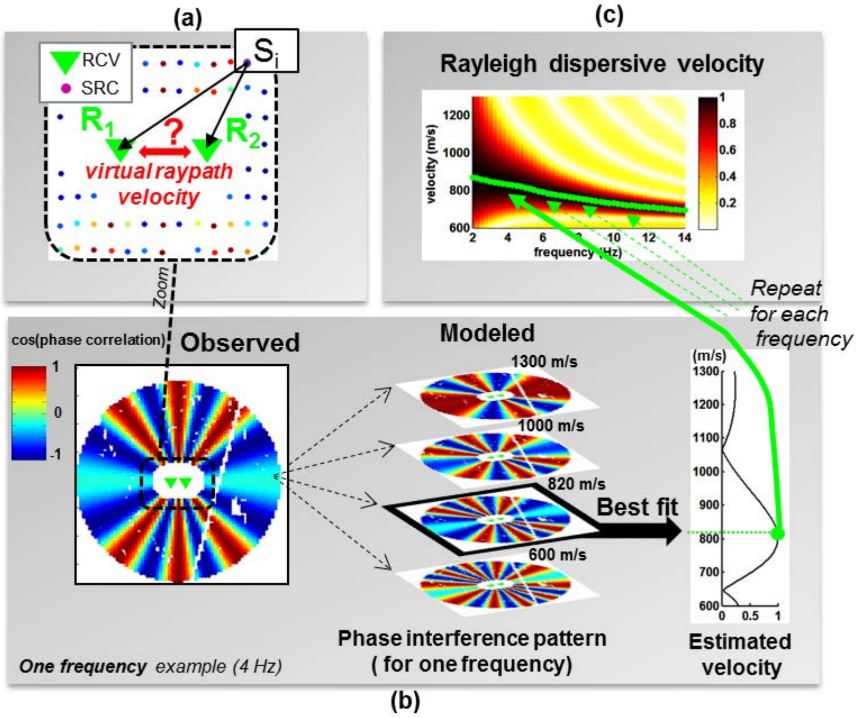

Figure 2 *Inversion principles for Rayleigh dispersive velocity estimation. Example of a receiver-receiver (R_1 and R_2 green triangles in (a)) phase interference pattern for a dense carpet of several sources S_i, obtained by cross-correlating for each source S_i the two corresponding S_iR_1 and S_iR_2 traces.*

As all sources (or receivers for a source-source virtual couple) within a selected radius on the order of a kilometer are considered, the estimation provides very good dispersion curve quality. For conventional approaches, only a small number of traces within the array are considered. The use of a wider array can help the estimation but would lead to an increase of detrimental velocity averaging over the array extension.

Proof of concept on synthetic dataset

In order to demonstrate our approach, a modelling and inversion workflow on synthetic seismic has been implemented on a subset of 9 tiles of a cross-spread geometry (Figure 3-c). A small anomaly with a faster velocity was introduced in a layered Vs model, providing after forward modelling a dispersive Rayleigh wave input model (Figure 3-a). The modelled seismic traces are then picked, for comparison, by a conventional array-based technique and by the virtual raypath approach described in this paper. The velocities estimated from surface wave tomography using the picked travel times (Figure 3-b, 3-c) show the ability of the virtual raypath approach to detect small velocity anomalies. Resolution of the estimated velocity becomes higher and is sensitive to the inter-receiver or inter-source distance (25 m), instead of to the interline distance (~ 200 m).

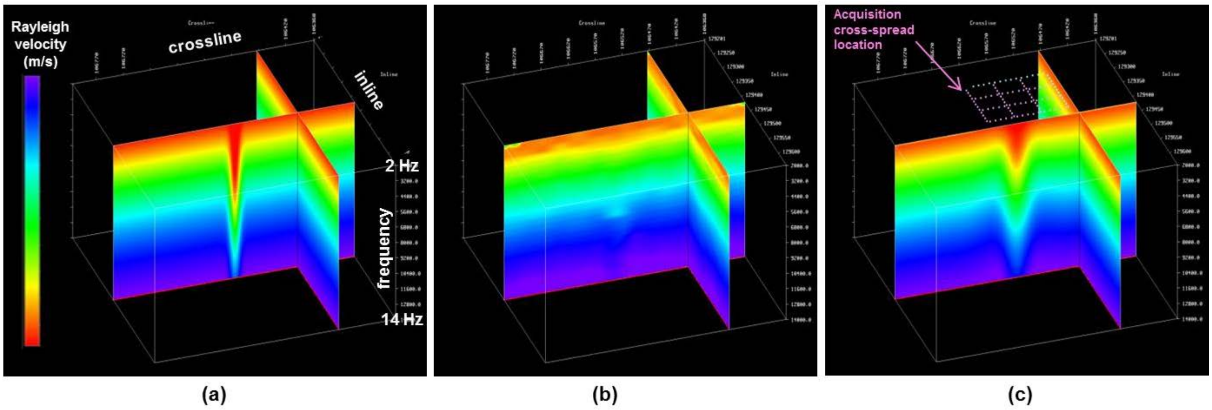

Figure 3 *Dispersive Rayleigh velocity cubes in [inline, crossline, frequency] domain. As an input model (a), a velocity anomaly with a size smaller than a cross-spread interline distance is introduced, similar to the one represented in Figure 1. A tomographic inversion result with array-based picking method using a conventional seismic hardly detects the anomaly (b), while tomographic result with virtual ray inversion better detects it (c).*

Illustration on a real 3D seismic dataset

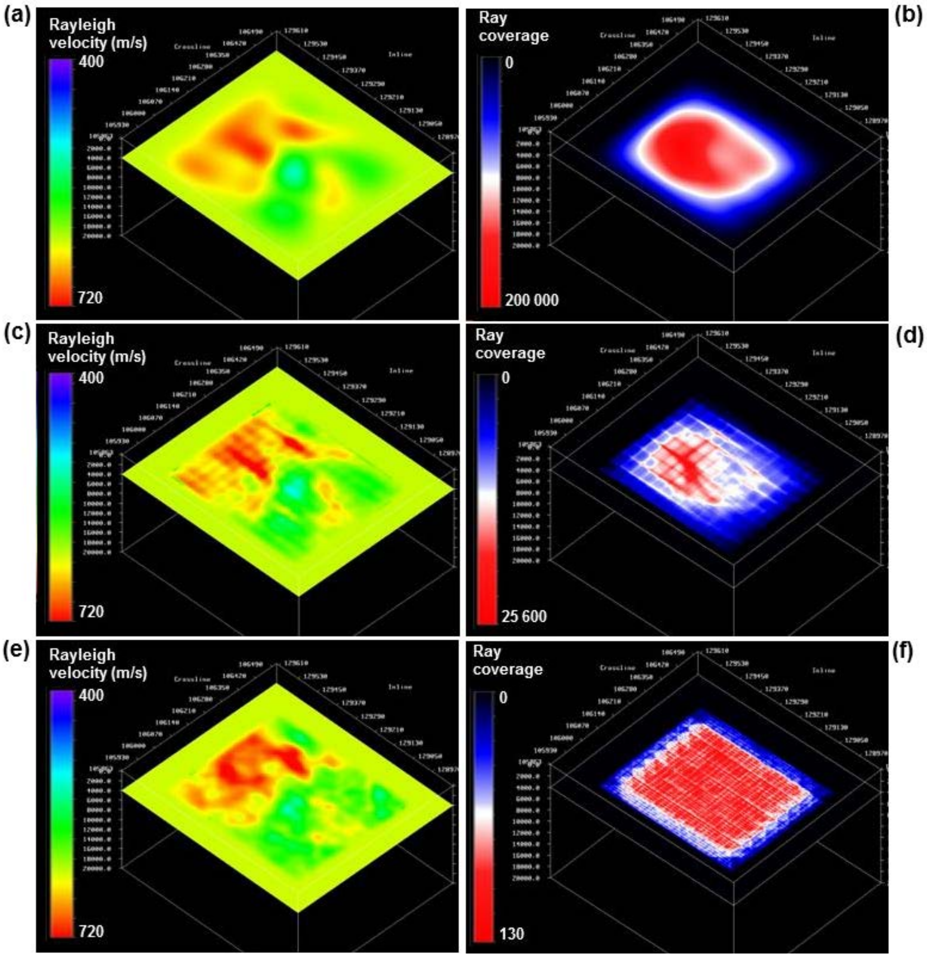

Figure 4 *Surface wave Rayleigh tomography slice at 4 Hz: a) with a classical 200 m inversion bin size using a conventional array based surface wave picking method, c) with a high resolution 20 m bin size using a conventional array based surface wave picking method, (e) with a high-resolution 20 m bin using virtual rays. The virtual raypath approach provides refined geological information and mitigates cross-spread acquisition footprints. The corresponding ray coverages after the tomographic inversion are shown in (b), (d) and (f).*

Our methodology is tested on a 9 km^2 selected area of a 3D Wide-Azimuth land survey acquired by PDO. The dense source dataset is decimated to a cross-spread geometry with a source inter-line spacing of 250 m, receiver interline spacing of 200 m, and a 50 m interstation spacing for both sources and receivers.

A conventional surface wave tomography using array based picks has a resolution determined by the 200 m interline spacing (Figure 4-a). Furthermore, if the surface wave tomography is performed with a 20 m resolution using the same picks, strong acquisition imprints related to inline and crossline preferential coverage clearly appear (Figure 4-c). This is confirmed by the coverage displays after tomography (Figure 4-b, 4-d). Conversely, with the virtual ray approach, the tomography result at 20 m resolution appears more geologically linked, demonstrating the gain in resolution (Figure 4-e). Despite the 200 times smaller number of virtual rays, when compared to conventional tomography approach, the final coverage confirms the benefits having a homogeneous sampling of the near surface, here virtually estimated (Figure 4-f). Identified challenges, such as multi-mode handling or strongly heterogeneous media, are similar to the concerns faced by array based inversions.

Conclusions

This paper describes a new approach which goes beyond the coverage and resolution limitation of conventional array based Rayleigh surface wave tomography. The approach is illustrated on a cross-spread geometry. This improvement has a positive impact on the shear wave velocity estimation workflow. It has been demonstrated on synthetics and a real 3D data test. A resolution of the order of the inter-receiver or inter-source distance appears feasible without strong acquisition pattern imprints over the surface wave tomographic result. This will allow better constraints for statics estimation, Vp-Vs inversion and near-surface geotechnical matters.

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