Wavefield separation using spatial wavefield gradient estimates

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1 Introduction

Land seismic data acquired at the Earth's surface are recordings of the superimposed upgoing (incident P or S) wave and two downgoing waves (the pure mode reflection and the mode-converted reflection) (Fig. 1). Mitigating the problem of wavefield interference at the free surface in order to retrieve true amplitude and phase information is crucial for subsurface characterisation and imaging.

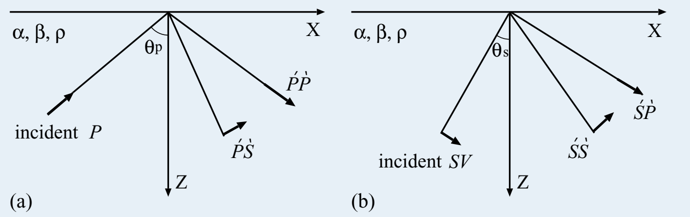

Fig. 1. Wavefield interference at the free surface for (a) an incident P-wave and (b) an incident S-wave.

2 Method

We propose an algorithm that removes the free surface effect for a wide range of incidence angles by up/down separation based on the elastodynamic representation theorem ([1]). The technique makes use of spatial wavefield gradient estimates from local receiver groups of densely spaced stations and does not require long acquisition arrays. The derived 2D space-frequency domain filters to isolate the upgoing horizontal (v_x^U) and vertical (v_z^U) waves are based on first and third order horizontal derivatives of the recorded wavefield components (v_x and v_z), scaled by frequency (ω) and the local P- and S-wave velocities (α and β):

$$v_x^U \approx \frac{1}{2}\left(v_x - \frac{i\alpha}{\omega}\left(1-\frac{2\beta}{\alpha}\right)\frac{\partial v_z}{\partial_x} + \frac{i\alpha}{\omega^3}\left(\frac{\alpha^2}{2} - 2\beta^2 + \frac{\beta^3}{\alpha}\right)\frac{\partial^3 v_z}{\partial_x^3}\right)$$

$$v_z^U \approx \frac{1}{2}\left(v_z + \frac{i\beta}{\omega}\left(1-\frac{2\beta}{\alpha}\right)\frac{\partial v_x}{\partial_x} - \frac{i\beta}{\omega^3}\left(\frac{\beta^2}{2} - 2\beta^2 + \alpha\beta\right)\frac{\partial^3 v_x}{\partial_x^3}\right)$$

no filter
0° incidence

1 filter term
> incidence angles

2 filter terms
>> incidence angles

3 Synthetic example 1 – homogeneous velocity model

An explosive source emitting a 50 Hz Ricker wavelet was placed 100 m below the free surface in a homogeneous medium with P- and S-wave velocities of 1800 m/s and 600 m/s, respectively. The fully recorded wavefield at the free surface comprises the direct upgoing P-wave, a downward reflected P-wave and a P-to-S converted wave, all overlapping each other. Fig. 1 shows the results for the different filter truncation orders in comparison to a reference solution consisting of the direct upgoing P-wave arrival only. Fig. 2 displays the corresponding percentage root-mean-square error (RMSE) against incidence angle. A significant improvement in isolating the desired upgoing P-wave can be observed by taking spatial gradients of the recorded wavefield into account, especially for the horizontal component. The accuracy of the wavefield separation algorithm increases with increasing order of spatial derivatives.

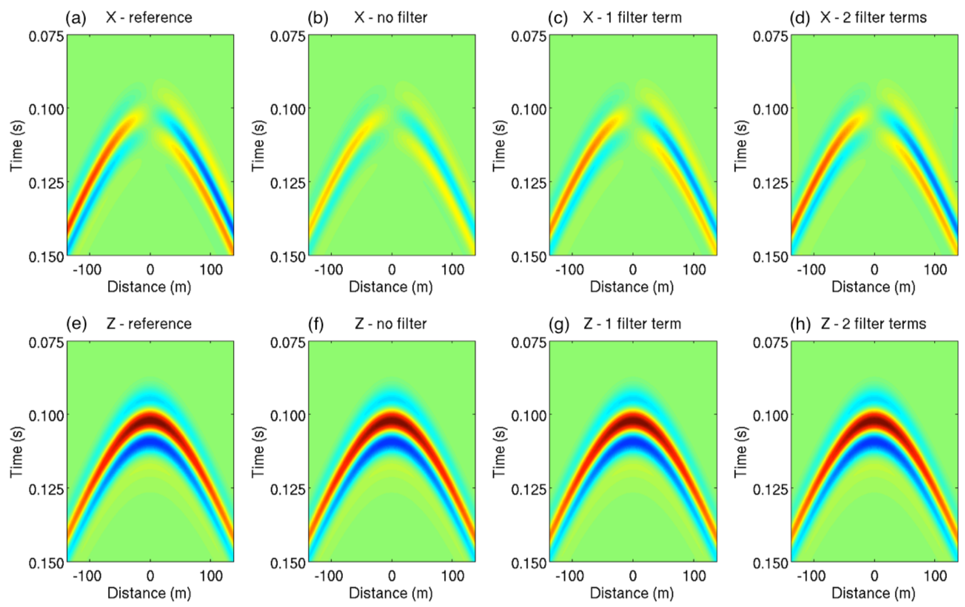

Fig. 2. Top: upgoing horizontal (X) wavefields with (a) the reference solution, (b) the result without filter, (c) the result using one filter term, and (d) the result using two filter terms. Bottom (e) to (h): same for upgoing vertical (Z) wavefields.

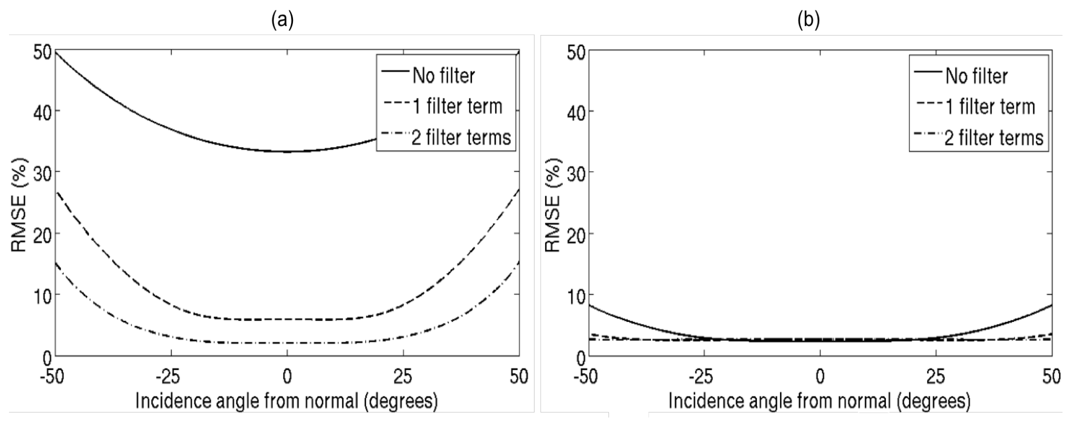

Fig. 3. Percentage RMSE versus incidence angle for the difference between the reference solution and the separation results in Fig. 2 for (a) the horizontal and (b) the vertical component.

4 Synthetic example 2 – velocity gradient model

In case of increasing P-wave velocities with depth, the velocity that leads to the optimal separation results is the one exactly at the free surface, irrespective of frequency (Fig. 4). This can be intuitively explained by the fact that the removal of the free surface effect is a frequency independent operation, whereby the composite particle motion due to reflections and mode conversions at the Earth's surface only depends on the velocities exactly at the recording locations. Hence, the accuracy is the same as for a homogeneous subsurface model.

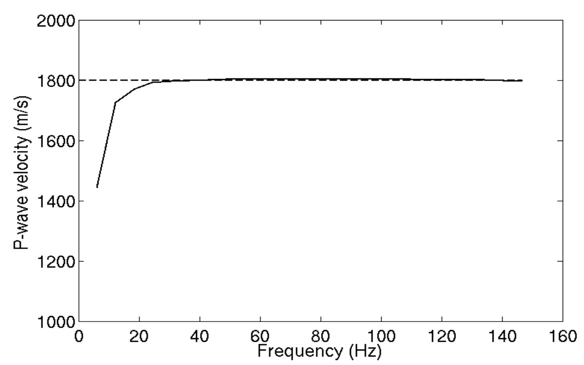

Fig. 4 Inverted optimal P-wave velocity as a function of frequency in case of a gradient velocity model.

5 Conclusions

We presented a method to isolate the upgoing wavefield from land surface seismic recordings, based on filters derived from spatial wavefield gradient estimates within local multicomponent receiver groups. Highly accurate amplitude and phase information can be extracted by incorporating increasing orders of horizontal derivatives of the recorded wavefield.

6 References

1. Robertsson, J. and Curtis, A (2002). Wavefield separation using densely deployed three-component single-sensor groups in land surface-seismic recordings. *Geophysics*, 67(5), 1624-1633.