Surface wave elimination by interferometry with nonlinear local filter

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Summary

We present a technique to eliminate the surface waves by an interferometry+nonlinear local filter (NLF). This technique consists of 3 steps: i) remove the surface waves by the NLF; ii) predict the residual surface waves and primaries by the interferometric method; iii) predict the surface waves by the NLF and remove the residual surface waves by a matched filter. Field data tests, for both 2D and 3D surveys, show that this technique effectively mitigates surface waves and preserves much of the reflection information.

Introduction

The surface waves coexist with and blur the reflection data, and can strongly degrade the result after processing steps such as AVO, DMO, velocity analysis, and prestack migration. An additional difficulty is that surface waves are often dispersive (Dobrin 1951), meaning that their phase velocity is frequency dependent. To make matters worse, the surface waves are badly sampled in space because of their short wavelengths. This makes it difficult to separate surface waves from the desired reflection data with conventional techniques, for example $f-k$ analysis. Although stacking is an effective way to eliminate the effect of surface waves, it can not improve the prestack data.

Several techniques have been proposed to remove surface waves from seismic records. Among these, are multichannel filtering (Galbraith and Wiggins, 1968), spectral balancing (Coruh and Costain, 1983), muting, $f-k$ filtering, linear frequency-modulated matched filter (Saatcilar and Camtez, 1988) and wavelet filter (Schuster and Sun 1993). All of these techniques are useful in surface wave suppression, although they remove too much useful information or left too much noise.

To overcome some of the liabilities of traditional surface waves filtering methods, I propose to eliminate the surface waves and minimize harm to the reflection data by using an interferometric method combined with a nonlinear local filter.

The Interferometry Prediction for surface waves

The key idea (Dong and Schuster, 2006) behind surface wave prediction by interferometry is that a surface wave can be modeled as

$$u(s, g) = A(s, g)e^{ikr_{sg}}. \quad (1)$$

where $u$ is the vertical component of particle velocity and $A(s, g)$ is the amplitude term that accounts for the source wavelet and geometrical spreading. Correlating traces at $g$ and $g'$ and summing over sources gives

$$\phi(g, g') = \sum_s u(g|s)\ast u(g'|s) = e^{ik|g-g'|} \sum_s A(g|s)A(g'|s). \quad (2)$$

Assuming $A(g|s).A(g'|s) > 0$, then correlation and summation over sources amplifies the surface wave signal. What about the prediction of body waves? Won’t they also be predicted by equation (2)? The answer is that every source position is a stationary source for surface waves, while there are only a finite number of source positions that are stationary for the generation of body wave reflection. Therefore using a few irregularly spaced source positions is unlikely to coincide with the stationary points for a specific body wave yet they will always be at the stationary points for prediction of surface waves. This means that predicted surface waves will be amplified relative to predicted body waves for sparse source distributions. The problem with 3D prediction of surface waves from 3D data is that the traces are irregularly spaced, and often aliased for surface wave recording. Therefore it is desirable to only select the source positions that are stationary with respect to the propagation path. This means we only use sources that roughly lie within a distance of $1/4\lambda$ of the line to be predicted, where $\lambda$ is the dominant wavelength of the surface waves. Still, it can be difficult to find enough sources to accurately predict the surface waves.

There is no perfect geometry for the 3D interferometric prediction of surface waves. We have to find a way to deal with the 3D problem. A simple solution is to convert the 3D problem to a 2D problem. First, we need to apply a nonlinear shift to the 3D seismic data to make the surface waves in each receiver line appear as a virtual linear event. Second, we to align the shifted traces of a receiver line to create virtual gathers. The 3D problem is now transformed into a virtual 2D problem. Figure 1 shows the process of a synthetic 3D data: a) represents
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3D seismic data in a receiver line; b) is the data after the time shift; c) is the surface waves predicted from b); d) is the data after removing the surface waves. Let \( d \) denote the distance between the source and the receiver line, let \( x \) denote the distance from the receiver to the center of the receiver line, as shown in Figure 1, so the nonlinear shift in time is:

\[
dt = \frac{\sqrt{d^2 + x^2} - x}{v},
\]

where \( v \) is the dominant velocity of the surface waves. After the nonlinear shift, the surface waves are still aliased. Applying the linear shift can weaken the aliasing. Figure 3 shows the workflow for 3D surface wave elimination.

Field data test

2D field data test

The data sets I used to demonstrate this method has both the shot and the receiver interval at 30 meters, and there are 240 traces per shot gather. The time sample is 4 milliseconds and the trace length is 2 seconds. Figure 4 shows field data with surface waves and reflection information (left) and the same data after removing the surface waves by the NLF (right). Comparing these two pictures, we can find that most of the surface waves are removed and we can discern the reflections. But there is still a large surface wave residual. It is difficult to completely eliminate the surface waves by the NLF because this filter relies on a high energy contrast between the signal and noise in the data.

Figure 5 shows the results of removing surface waves using the NLF and using the interferometry + NLF for 2 iterations. Comparing these two pictures, we can find that there is less surface wave energy in the right picture compared to the left picture. The interferometry + NLF can successfully mitigate the residual surface waves with lower energy! Comparing the picture in the left of Figure 4 and the one in the right of Figure 5, it is obvious that much of the surface wave energy is removed and the reflections are clearly revealed.

Figure 6 shows the surface waves predicted using the NLF from the original data (left) and the residual surface waves (the remaining surface waves after subtracting the surface waves predicted in the left figure) predicted using the interferometry + NLF method for 2 iterations. Comparing these two figures, the obvious difference is that the surface waves with lower energy can not be predicted by the NLF but were predicted and mitigated by the interferometry + NLF method. Figure 7 is the result of removing surface waves using a \( f - k \) filter and using interferometry + NLF for 2 iterations. Comparing the upper parts of these pictures, they almost have the same information: the reflections are clear and continuous.
But for the lower parts of these two pictures, we can find that the reflections on the right are continuous but the reflections on the left are discontinuous. The reason for this is that the energy in the lower part is much less than that in the upper part. The $f-k$ method eliminated too much of the energy so that the reflections are damaged. Figure 8 shows the surface waves predicted by $f-k$ (left) and (right) by the interferometry + NLF for 2 iterations. It’s obvious the $f-k$ method predicted too much reflection energy and the interferometry method predicted much less than the former.

Figure 4: A CSG from Saudi-Aramco (left) before and (right) after removing surface waves with the nonlinear local filter.

Figure 5: Result of removing surface waves using nonlinear local filter (left) and (right) using the Int.+NLF method for 2 iterations.

3D field data example

Figure 9 depicts a 3D field data set from China. One shot gather contains 14 receiver lines and the distance between any two neighboring lines is 160 meters. Figure 10 is the result after eliminating the surface waves from Figure 9 with the nonlinear shift+median filter+interferometry technique. From Figure 10, we can see that the strong surface waves are eliminated. We just show the detail of line 5 as an example. Figures 11 depicts the seismogram of receiver lines 5 before and after removing the surface waves. We can see that the surface waves are eliminated
and the reflection details are obvious.

![Figure 9: Original 3D data with surface waves.](image)

![Figure 10: 3D data after removing surface waves.](image)

**Figure 9:** Original 3D data with surface waves.

**Figure 10:** 3D data after removing surface waves.

**Conclusions**

In this paper, I show how to combine a local nonlinear filter with interferometric prediction of surface wave data. The application of this theory is shown. The interferometric method can predict surface waves but not exactly, which means that you cannot just use the interferometric method to predict the surface waves and subtract them. When I iteratively apply the interferometry method combined with a nonlinear local filter, it more effectively eliminates the surface waves. Iterations are needed because filters can eliminate a large portion of the surface waves but a significant residual remains. However, the interferometric method can amplify the residuals and improve the prediction-subtraction process for each iteration. The Saudi Aramco data is used to show that this new method can eliminate the surface waves clearly without damaging the reflection information. For this data set, 2 iterations of the interferometry method are enough to mitigate the surface waves.

The technique applied to 2D data can also be applied to 3D data. Traces in each gather must be time shifted so that the surface waves have a linear moveout and this is a novelty. By transforming the shifted data to be virtual 2D gathers in a line, we can apply the 2D interferometry technique to the virtual 2D data. The results show that the nonlinear shift+NLF+interferometry technique can successfully eliminate the surface waves of 3D data. The problem with this method is that: 1) the angle between the moveouts of the signal and noise cannot be too small. This will make the result of the nonlinear local filter worse. 2) if too many of the reflections have a linear moveout after the time shift, the interferometry method will not be so effective.

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