

VSP wave separation by adaptive masking filters

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Abstract

In vertical seismic profiling (VSP) data processing, the first step might be to separate the down-going wavefield from the up-going wavefield. When using a masking filter for VSP wave separation, there are difficulties associated with two termination ends of the up-going waves. A critical challenge is how the masking filter can restore the energy tails, the edge effect associated with these terminations uniquely exist in VSP data. An effective strategy is to implement masking filters in both τ - p and f - k domain sequentially. Meanwhile it uses a median filter, producing a clean but smooth version of the down-going wavefield, used as a reference data set for designing the masking filter. The masking filter is implemented adaptively and iteratively, gradually restoring the energy tails cut-out by any surgical mute. While the τ - p and the f - k domain masking filters target different depth ranges of VSP, this combination strategy can accurately perform in wave separation from field VSP data.

Keywords: wave separation, masking filter, f - k filter, τ - p filter, VSP

(Some figures may appear in colour only in the online journal)

Introduction

Vertical seismic profiling (VSP) data, which provide high-resolution subsurface information in the vicinity of target reservoirs, have been used for estimating the interval velocity and the interval attenuation parameters (Pevzner *et al* 2012, Ahmadi *et al* 2013, Wang 2014). One may first need to separate the down-going wavefield from the up-going wavefield, to exploit the full potential of VSP data.

There are several effective approaches used in practice for VSP wavefield separation. A f - k filter utilizes the difference in apparent velocities of down- and up-going wavefields (Christie *et al* 1983) but might not be able to accurately separate these wavefields, because the energy at different f - k quadrants has overlap (Kommedal and Tjøstheim 1989). A median filter, which often can do a better job, is fundamentally a sliding average along a single curve, such as the first arrival time versus depth. This may be referred to as median filtering after flattening. However, because of the averaging effect, the median filter may change the individual waveform.

A Radon transform method for wave separation exploits the linear coherence of wavefields, which have different apparent velocities or different curvatures, and produces a theoretically better separation result than the f - k filter and the median filter (Moon *et al* 1986). The linear Radon transform is often referred to as the τ - p transform, where τ and p are the intercept time and the slope respectively of a linear event.

One of adaptive approaches is called masking filter, which first uses a reference data set to generate a masker, and then processes the original data image accordingly. *Adaptive* not only means an irregular shape of the masker, closely following the image of the reference data set, but also reflects the spatially variable weights of the filter, assigned based on the image similarity between the raw and the reference data sets. The designed non-linear filter depends on the input amplitudes (Zhou and Greenhalgh 1994) and the iterative approach will redefine the rejection/muting area according the amplitude distribution. The masking filter was used to separate seismic primaries from multiple reflections in surface seismic reflection data (Zhou and Greenhalgh 1994, Wang 2003).

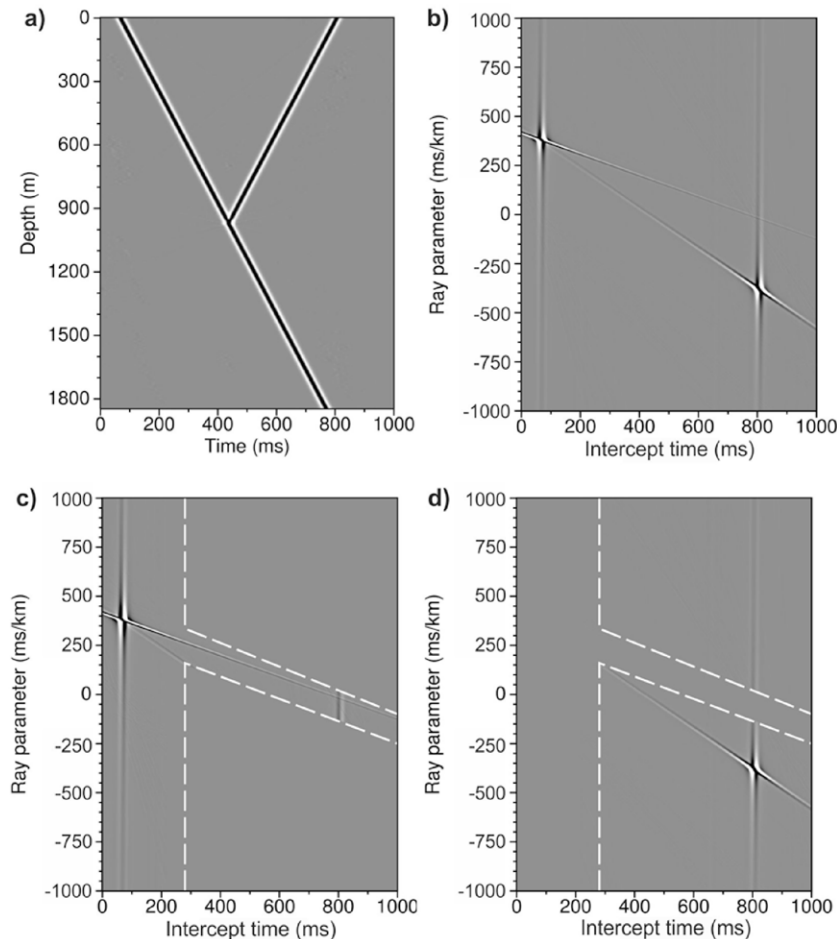


Figure 1. (a) A simple synthetic VSP data set with a single down-going and a single up-going event. (b) The Radon image, showing the effect due to spatial truncations in the t - x domain. In this synthetic example, the time interval is $\Delta t = \Delta \tau = 1$ ms, the depth interval is $\Delta x = 5$ m, and the interval of the ray parameter is $\Delta p = 5$ ms km⁻¹. (c) The Radon image of VSP down-going waves obtained by surgical muting. (d) The Radon image of VSP up-going waves obtained by surgical muting. The muting (white dashed lines in figures (c) and (d)) has cut out the tails of the τ - p response causing energy to leak into the opposite territory.

It had effectively separated, either in the f - k domain or the τ - p domain, the cross-hatched tails, the edge effect of the multiple reflections and the primary reflections.

However, when using this masking filter for VSP wave separation, there are two challenges, related to two ends of the up-going waves (figure 1). First, the up-going waves are relatively weak, in contrast to the down-going waves, and thus the edge effects associated with the termination of the up-going waves have very weak energy. Once those weak-energy tails are cut out by any surgical mute, this presents a critical difficulty for a masking filter to restore them. Second, no energy can exist in front of VSP first arrivals (figure 1), but wave separation techniques always generate some artifacts in that region. This is because either the f - k transform or the τ - p transform implicitly assumes continuity of linear events in t - x space. This assumption is in contrast to the fact that the up-going waves terminate like a step-function at wherever the first arrival is. It makes the task of the masking filter more difficult than in the case of separation of surface reflection seismic data.

Hence, the prime objective of this paper is to alleviate the edge effect associated with VSP up-going waves. This edge effect is uniquely related to two truncations in VSP, and differs

from that in surface seismic data. Masking filters in the τ - p domain and the f - k domain are effective in different portions of the VSP data. Therefore, a sequential application of these two masking filters is a natural choice for VSP wave separation. In addition, the median filter can produce a smooth and clean version of the down-going wavefield. This over-filtered version is used as the reference data set, needed in the adaptive masking filter, for generating the artificial energy tails. The strategy combining the median filter and the τ - p domain and the f - k domain masking filters will be proved to be effective in wave separation from field VSP data.

VSP wavefield separation strategy

This paper presents an effective strategy, using masking filters, for VSP wavefield separation as what follows.

- (1) Using a τ - p domain masking filter to partially remove VSP up-going waves but to keep all down-going waves untouched. This preprocessed wavefield $A(t, x)$ will be processed further by the following f - k domain masking filter.

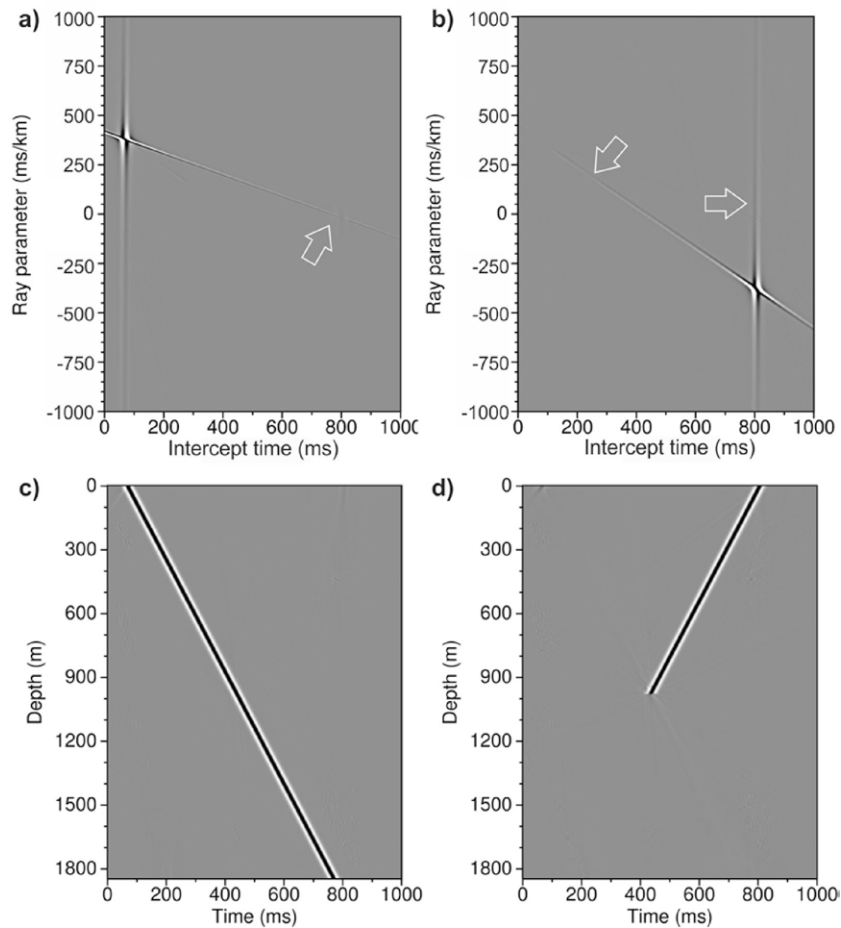


Figure 2. The adaptive surgical mute by the Radon-domain masking filter. (a) and (b) The Radon image of VSP down-going and up-going waves obtained by the masking filter. (c) and (d) VSP down-going and up-going waves generated by inverse τ - p transform. These results are produced by applying the masking filter five times.

- (2) Applying a median filter to $A(t, x)$, to produce a smooth version of VSP down-going wavefield, on which all of the up-going wave energy are eliminated completely. This smooth data set $B(t, x)$ will be used as a reference data set for designing the f - k domain masking filter.
- (3) Applying the f - k domain masking filter to $A(t, x)$, to gently update the down-going wavefield $B(t, x)$.
- (4) Using this newly recovered down-going wavefield as the reference data set $B(t, x)$, to design the f - k domain masking filter, and performing step 3 iteratively.
- (5) Finally, when the down-going wavefield $B(t, x)$ is fully recovered, subtracting it from the raw VSP data set, to obtain the final up-going wavefield.

τ - p domain masking filter

The first step of the strategy is an application of the τ - p domain masking filter.

The linear Radon transform is implemented as an inverse problem. Consider the inverse τ - p transform,

$$d(t, x_k) = \sum_{j=1}^M m(\tau_i = t - p_j x_k, p_j), \quad (1)$$

where $d(t, x_k)$ is a seismic trace in the t - x domain, x_k is the source-receiver offset, τ_i is the intercept time, p_j is the ray parameter, $m(\tau_i, p_j)$ is the image in the Radon transform domain, and M is the total number of p traces. In the frequency domain, it becomes (Tatham 1984)

$$d(f, x_k) = \sum_{j=1}^M m(f, p_j) e^{-i2\pi p_j x_k}, \quad (2)$$

where f is the frequency in Hz. This is a system of linear equations. Given seismic data $d(f, x_k)$, the Radon image $m(f, p_j)$ can be obtained by solving this system. The Radon image for each frequency is solved independently using a generalized least-squares method (Beylkin 1987, Wang 2002a).

Linear events, such as VSP down-going and up-going waves, with different apparent velocities in the t - x domain should be transformed ideally to points in the τ - p domain. However, because of limited spatial aperture and the edge effect, their Radon images commonly have cross-hatching linear effects. For a simple synthetic VSP gather, shown in figure 1(a), after the Radon transform, both the down-going energy (at the intercept time 80 ms) and the up-going wave energy (at the intercept time 800 ms) are well focused at $p \approx \pm 380 \text{ ms km}^{-1}$. But the tails of the up-going wavefield

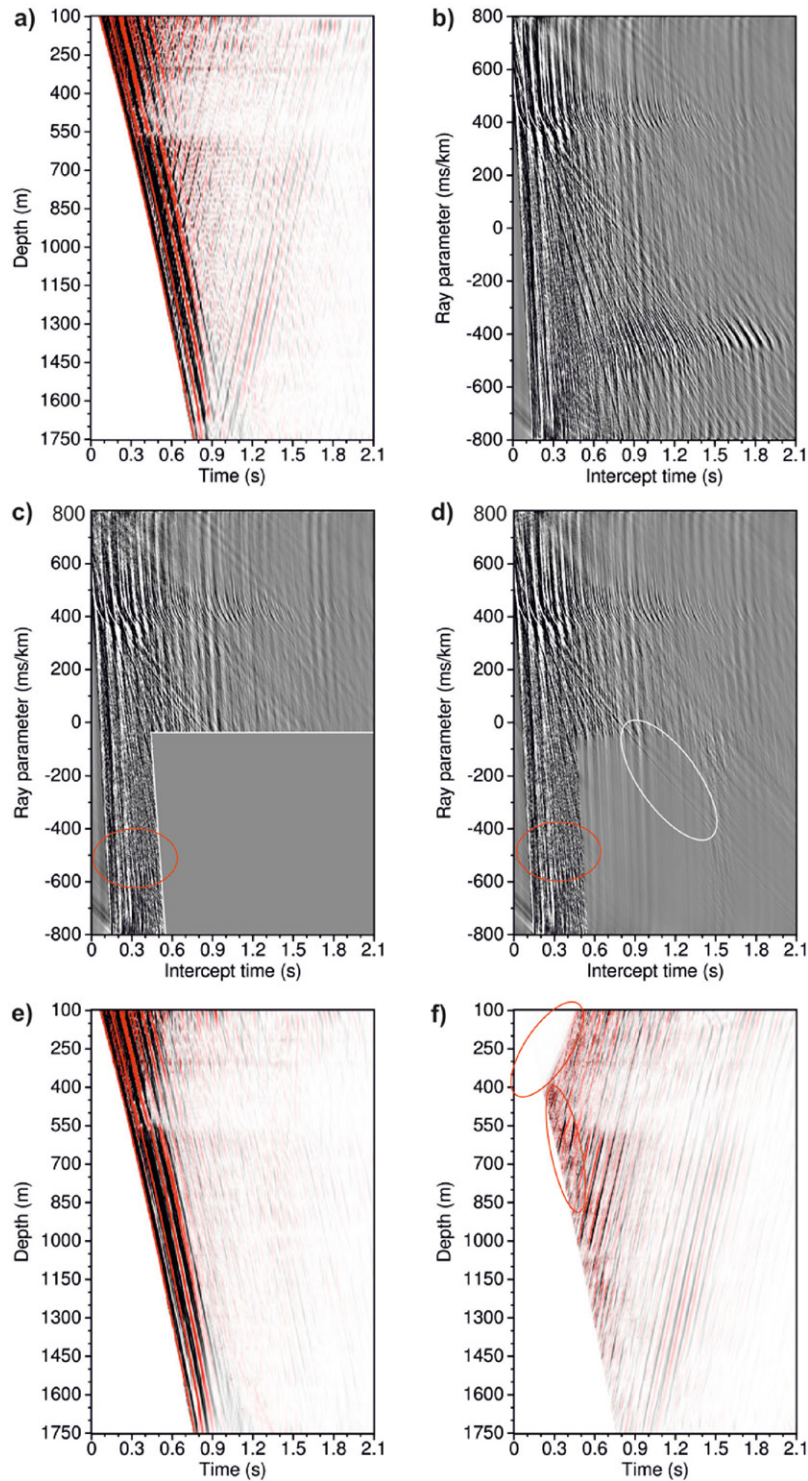


Figure 3. (a) A field VSP data set. Receivers are placed in a vertical borehole over the depth range from 100 to 1750 m. (b) The Radon image of the VSP wavefield. (c) The Radon image after surgical muting. (d) The Radon image after the adaptive mute using the masking filter. (e) and (f) The up- and down-going wavefields, obtained by adaptive muting in the Radon image.

are overlapping with the tails of the down-going wavefield. This is a significant difficulty that we confront within VSP wavefield separation.

Theoretically, x -direction tapering before τ - p transform can improve the τ - p domain image, but will not work for VSP data. First, tapering will alter the waveforms near to two ends in the x direction. Second, tapering cannot be applied to the up-going waves which terminate at the first arrival times.

Performing a surgical mute on the Radon image (white dashed lines in figures 1(c) and (d)), and then the inverse τ - p transform, we expect to separate the down-going and up-going wavefields. However, surgical muting has cut out the tails of the τ - p response, causing energy to leak into the opposite territory.

In order to preserve these tails of the up-going wave energy, a masking filter can be applied in a sequence as what follows.

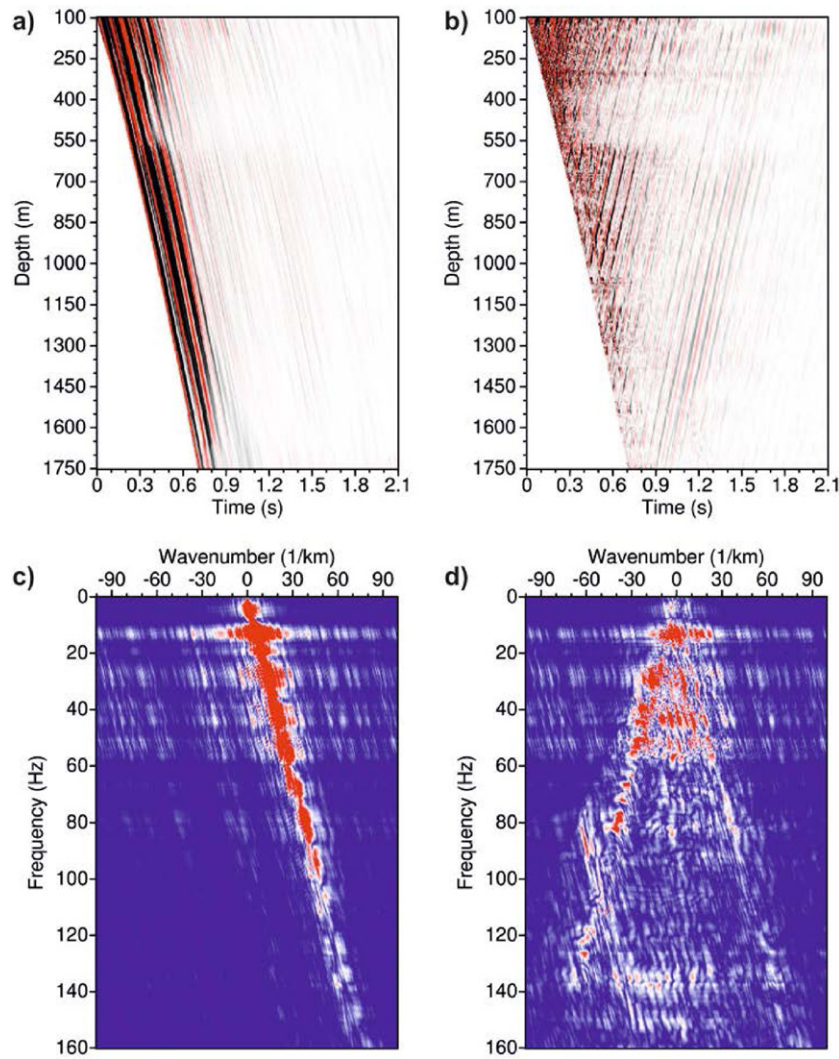


Figure 4. The median filter. (a) and (b) VSP down-going and up-going wavefields obtained by the median filter. (c) and (d) The f - k images of the down-going and up-going wavefields. It has clearly removed the up-going wavefield from the down-going wavefield (a) and (c).

- (1) Performing inverse τ - p transform over the τ - p image shown in figure 1(d), to produce a reference data set $B(t, x)$;
- (2) Performing the τ - p transform over $B(t, x)$, to generate the Radon image $B(\tau, p)$ with artifacts;
- (3) Utilizing the Radon image $B(\tau, p)$ with artifacts to design a τ - p domain masker;
- (4) Applying this mask filter to mute the original Radon image $A(\tau, p)$, to recover any tails existing in the opposite territory.

The masking filter is designed as (Zhou and Greenhalgh 1996, Wang 2003)

$$g(\tau, p) = 1 - \frac{1}{\sqrt{1 + \left(\frac{B(\tau, p)}{\varepsilon A(\tau, p)} \right)^{2\eta}}}, \quad (3)$$

where $A(\tau, p)$ is the Radon image of the original VSP data (including both the up-going and down-going waves), $B(\tau, p)$ is the Radon image of the reference data set, ε is a parameter for balancing the amplitudes between the image

$A(\tau, p)$ and the image $B(\tau, p)$, and η is a parameter controlling the sharpness of the masking filter. The artifacts in $B(\tau, p)$ are the important parts of the masker, for successfully recovering the energy leakage that was cut out (arrows in figures 2(a) and (b)). Applying the masking filter to the Radon image $A(\tau, p)$ of the entire VSP wavefield will result in cleaner wave separations (figures 2(c) and (d)). In this synthetic example, the masking filter is applied iteratively for five times.

However, when applying this method to a field VSP data set, the wave separation result is far from satisfactory. Figure 3(a) displays a field VSP data set, in which receivers are placed in a vertical borehole at depths from 100 to 1750 m, with 5 m depth interval. A source is placed 55 m away horizontally from the top of the borehole. This is a typical VSP data set, which has much higher signal-to-noise ratio than any surface seismic data in the same area.

Before the τ - p transform, VSP traces $d(t, x)$ are linearly interpolated along the depth direction, using an f - x interpolation method (Wang 2002b). The depth interval is halved ($\Delta x = 2.5$ m). The time axis has also been resampled to

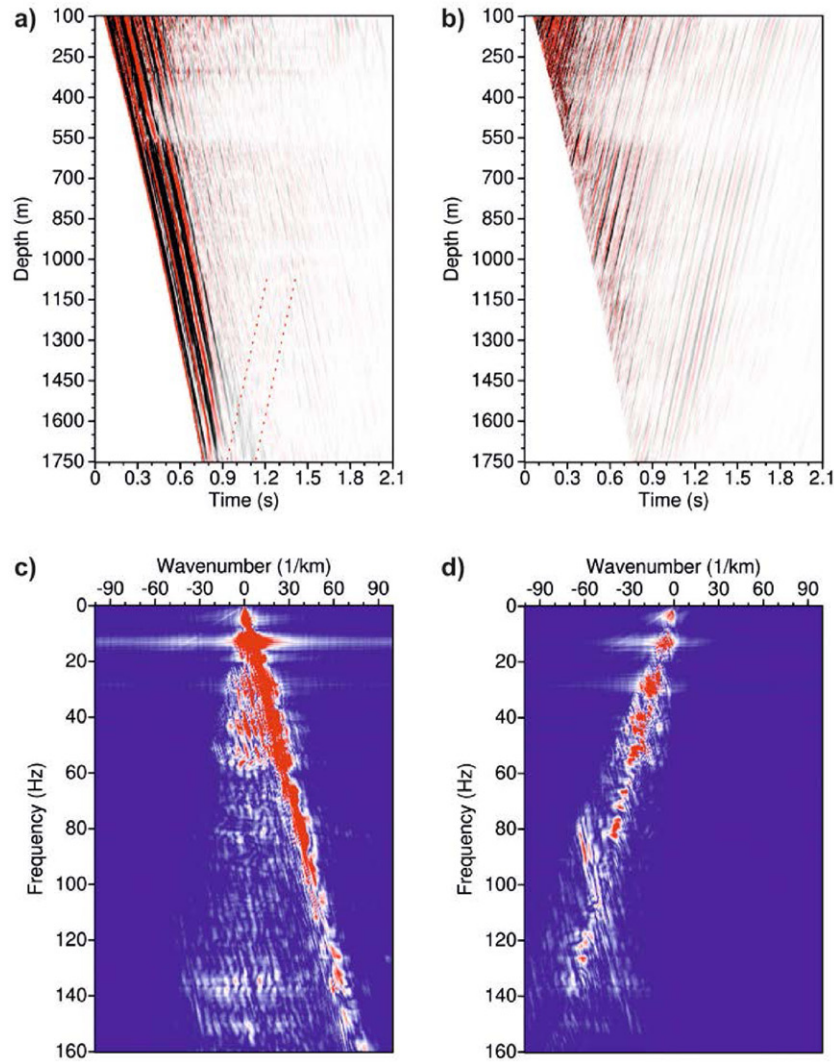


Figure 5. The f - k filter. (a) and (b) VSP down-going and up-going wavefields obtained by the f - k filter. (c) and (d) The f - k images of the down-going and up-going wavefields. A simple fan filter cannot effectively remove all up-going waves (marked by dashed lines) reflected from the bottom of borehole.

$\Delta t = 2$ ms. The maximum p value should be (Greenhalgh *et al* 1990, Wang and Houseman 1997)

$$p_{\max} = \frac{k_{\text{Nyq}}}{f_{\text{Nyq}}}, \quad (4)$$

where f_{Nyq} and k_{Nyq} are the Nyquist frequency and the Nyquist wavenumber, respectively. In this case, the p value is set between ± 800 ms km $^{-1}$.

Figure 3(b) is the Radon image of linear τ - p transform. Ideally, the down-going and up-going wave energies should be focused at $p \approx \pm 400$ ms km $^{-1}$. But it is very difficult to choose a successful mute on the Radon image, to separate the up-going wave energy from the down-going wave energy. After surgical muting (figure 3(c)), attempting to mute out the up-going waves, the tails of the down-going waves have also been cut out. After iterative application of the masking filter, these tails have been slowly recovered (highlighted with a white ellipse in figure 3(d)).

The down-going wavefield (figure 3(e)) can now be obtained by an inverse τ - p transform. However, subtracting

it from the original VSP data set, the up-going wavefield (figure 3(f)) shows some residuals of the down-going waves (within a red ellipse). Note that the up-going waves disappear at the very shallow depth. This is because the intercept times (at depth zero) of the up-going and down-going wavefields in this shallow part are close each other, and the up-going waves are mixed in the strong image of down-going waves in the τ - p domain (highlighted by red ellipses in figures 3(c) and (d)).

For the deep section, the τ - p filter can have a satisfactory separation of the up-going wavefield from the down-going wavefield. This is because, in deep regain, two wavefields have a clear difference in the intercept time τ (at depth zero).

F-k domain masking filter

Alternatively, we try to implement the masking filter in the f - k domain for wavefield separation. The masking filter in the f - k domain can be expressed as (Zhou and Greenhalgh 1994)

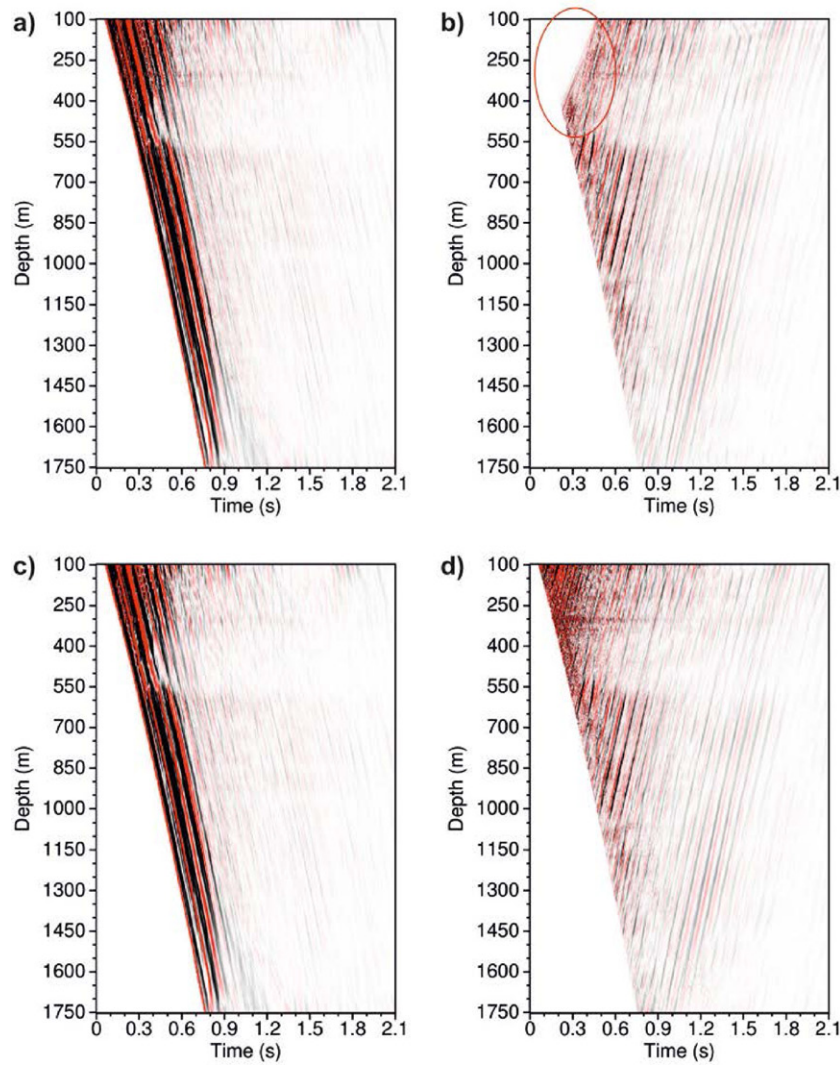


Figure 6. The f - k domain adaptive masking filter. (a) and (b) The down-going and up-going wavefields, obtained by the f - k domain adaptive masking filter and using the raw VSP data as the input data set. (c) and (d) The down-going and up-going wavefields, obtained by the f - k domain adaptive masking filter but using the τ - p domain surgically muted down-going wavefield as the input data set.

$$g(f, k) = 1 - \frac{1}{\sqrt{1 + \left(\frac{B(f, k)}{\varepsilon A(f, k)} \right)^{2\eta}}}, \quad (5)$$

The quality of wave separation is determined by two critical factors: the quality of the reference data set $B(t, x)$, used to generate the masking filter, and the quality of the input data set $A(t, x)$.

The reference data set is generated by median filtering. It is performed along the down-going waves first break times, with respect to the depth, and produces the down-going wavefield (figure 4(a)). The subtraction between the raw VSP data set and the down-going wavefield is treated as the up-going wavefield (figure 4(b)). Figures 4(c) and (d) are the f - k images of the corresponding down-going and up-going wavefields. In the f - k domain, the down-going and up-going wavefields have much simpler patterns than the images in the τ - p domain.

Figure 4 demonstrates that the median filtered down-going wavefield does not have any up-going wave residual.

Particularly, it has clearly removed the up-going wavefield at shallow depth. However, the down-going wavefield seems too smooth to keep the original waveforms. This can be observed from either the t - x domain or τ - p domain image of the up-going wavefield (figures 4(b) and (d)), on which a certain amount of down-going wave energy is evident.

For the sake of comparison, we also test the f - k filter and display the down-going and up-going wavefields and their f - k images in figure 5. In the f - k domain, linear coherent events can be separated according to different apparent velocity. The separated down-going wavefield (figure 5(a)) obtained by the f - k filter has kept the waveforms better than the median filter (figure 4(a)). But, a simple fan filter cannot effectively remove all up-going waves (marked by dashed lines) reflected from the bottom of borehole. The remaining up-going wave energy in the f - k image is close to the origin of the wavenumber axis (figure 5(c)), and this part of the energy is difficult to separate from the down-going wave energy.

We notice that the median filtered down-going wavefield image (figure 4(c)) has less up-going wave energy left

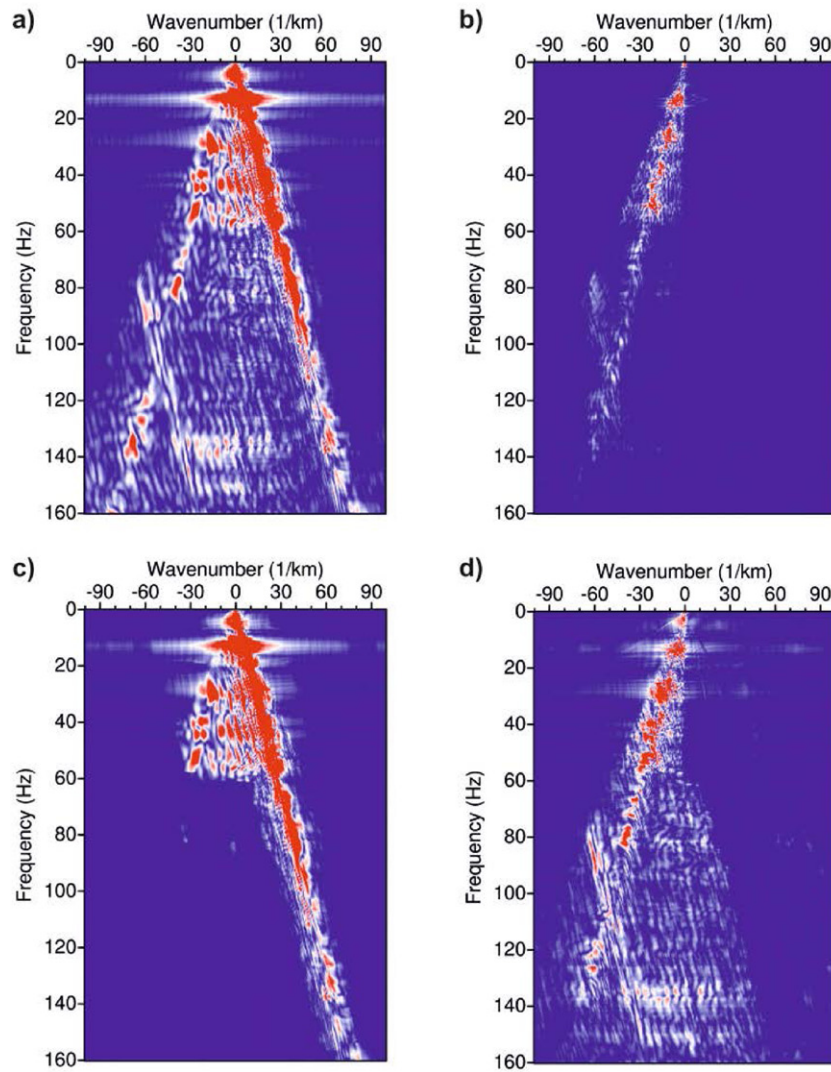


Figure 7. (a) and (b) The f - k images of the down-going and up-going wavefields (figures 3(e) and (f)), obtained by the τ - p domain surgical mute. (c) and (d) The f - k images of the down-going and up-going wavefields (figures 6(c) and (d)), obtained by the f - k domain adaptive masking filter and using the τ - p domain surgically muted down-going wavefield as the ‘original data set’.

in the negative wavenumber area, although considerable down-going wave energy remains in the up-going wavefield. Therefore, we decide to use median filtered down-going wavefield as the reference data set $B(t, x)$, for designing a masking filter.

For the input data set $A(t, x)$, to be used in the f - k domain masking filter, first we test the raw VSP data set as the input data set, and then we use the τ - p domain surgically muted down-going wavefield as the input data set.

Figure 6 demonstrates the effectiveness of the f - k domain adaptive masking filter, using these two types of the input data set. Figures 6(a) and (b) are the resultant wavefields when using the raw field VSP as the input data set. Figures 6(c) and (d) are the separated wavefields when using the τ - p domain surgically muted down-going wavefield (figure 3(e)) as the input data set.

Obviously, the second scheme is better than the first scheme. In the first scheme it is difficult to separate two wavefields in the shallow part (marked by an ellipse in figure 6(b)),

but the second scheme has done an excellent job. The up-going waves in figure 6(d) show much stronger energy than those in figure 6(b). It indicates that figure 6(c) has removed the up-going waves completely and figure 6(a) has not done so.

The masking filter is implemented adaptively and iteratively. In each iteration, down-going wavefield produced in the previous iteration is used as a new reference data set for designing the filter, and after filtering, the residual energy in the front of VSP first arrivals is also evaluated. Iteration stops when this residual energy is smaller than a pre-set threshold. In this field data example, the f - k domain masking filter is applied three times.

In the masking filter application to the field VSP data set, the sharpness parameter η is not so critical. However, the ε parameter which balances the amplitudes between the images $A(f, k)$ and $B(f, k)$ needs to be tested, ensuring the iteration process converges, so that the residual energy in the front area of VSP first arrivals in the next iteration is lesser than the current iteration. We set $\varepsilon = 0.4$ and $\eta = 1$ throughout this paper.

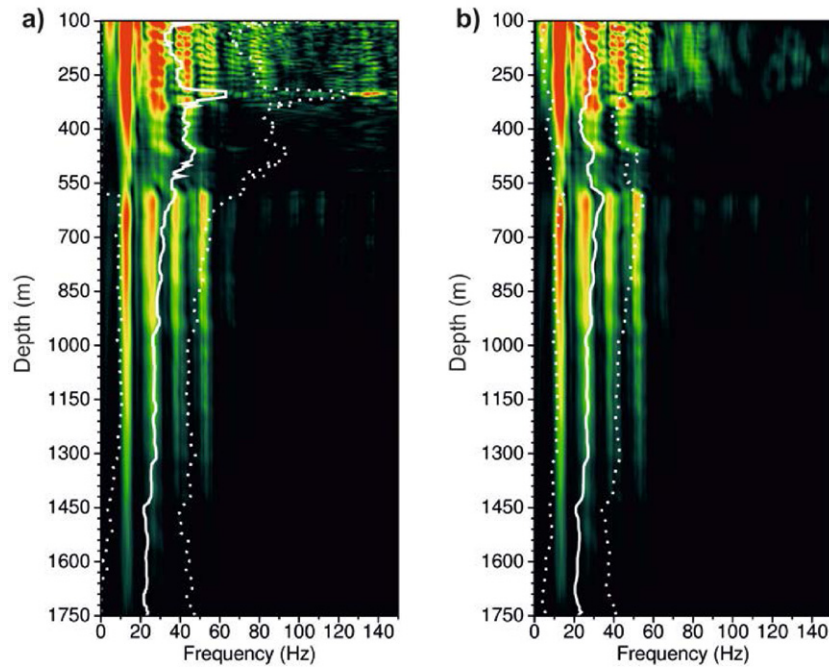


Figure 8. (a) The depth-frequency spectrum of the τ - p domain masking filtered down-going wavefield. (b) The depth-frequency spectrum of the f - k domain masking filtered down-going wavefield. The mean frequency values (the solid white curve) and the deviations (two dotted curves) are more consistent in the final down-going wavefield (figure (b)) than that in the input data set (figure (a)).

Masking filters in τ - p domain versus f - k domain

Figure 7 demonstrates the improvement made by the f - k domain masking filter. Figures 7(a) and (b) are the f - k images of the τ - p domain adaptive surgical muting (figures 3(e) and (f)), and figures 7(c) and (d) are the f - k images of the f - k domain adaptive surgical muting (figures 6(c) and (d)), which uses the τ - p domain adaptive surgically muted down-going wavefield (figure 3(e)) as the input data set. We see that much less energy of the up-going waves is leftover in the negative wavenumber area in the f - k image of the down-going wavefield, and more energy is recovered in the f - k image of the up-going wavefield.

Figure 8 compares frequency spectra dynamically along the depth. Figure 8(a) is the depth-frequency spectrum of the τ - p domain masking filtered down-going wavefield, and figure 8(b) is the depth-frequency spectrum of the f - k domain masking filtered down-going wavefield. The former is treated as the input data set in the latter f - k domain masking filter. In each of these spectra, the solid white curve defines the mean frequency, and two dotted curves indicate the deviation. The mean frequency (f_m) and the deviation (f_σ) are calculated by (Wang 2015)

$$f_m = \frac{\sum_f f A^2(f)}{\sum_f A^2(f)}, \quad f_\sigma = \left(\frac{\sum_f (f - f_m)^2 A^2(f)}{\sum_f A^2(f)} \right)^{1/2}. \quad (6)$$

where f is the frequency in Hz, and $A^2(f)$ is the power spectrum. The mean frequency directly reflects the central frequency, and the deviation is related to the bandwidth (Wang 2015). The mean frequency values, and the deviations, in

the shallow half-depth are more consistent in figure 8(b), the image of the final down-going wavefield, than that in figure 8(a). This consistence suggests that there are less up-going wave residuals leftover in the down-going wavefield, or more accurate recovery of the down-going waves through iterative use of the masking filter in the f - k domain.

Conclusions

In order to effectively separate VSP down-going and up-going waves, we have combined the τ - p domain masking filter, the median filter, and the f - k domain masking filter in a dynamic manner. The main processing steps are first to partially remove the up-going waves by using the τ - p domain filter, and then to completely eliminate the up-going waves by using the f - k domain masking filter. For designing the masking filter, a reference data set is generated with the median filter.

The τ - p filter can have a good separation of the up-going wavefield from the down-going wavefield, especially for the deep section in which regain two wavefields have a clear difference in the intercept time τ (at depth zero). The median filter can eliminate all up-going waves but produce a smooth down-going wavefield. Finally, the f - k domain masking filter can perform a very good separation of the up-going waves generated from reflectors within the entire depth range of VSP acquisition.

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