Introduction to vector-processing techniques for multi-component seismic exploration

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SUMMARY

Conventional multi-component seismic analysis simply relies on appropriate component selection to provide P- and S-wave images. However, this ignores the potential cross-contamination of P-wave energy on the horizontal components, and S-wave energy on the vertical component that may occur in certain geological situations.

Where wavefield cross-contamination occurs, there is potential to achieve cleaner P- and S-wave images by more fully exploiting the true vector nature of multi-component seismic data. Vector processing for exploration-scale data typically combines frequency and slowness information, together with particle motion, to distinguish different wave types. Three such multi-trace, multi-component wavefield separation schemes, termed MUSIC, IWSA and PIM, are considered here. These vector techniques all utilise a parametric approach whereby wavefield slowness and polarisation are modelled simultaneously in the frequency domain. The PIM algorithm is considered to be the most generally useful of the three algorithms.

Synthetic and ocean-bottom data examples are used to demonstrate practical issues relating to the use of these vector separation schemes. In cases where there is significant cross-contamination, vector wavefield separation produces P- and S-wave records that differ significantly from the vertical and horizontal components, respectively. Where cross-contamination is less problematic, production vector processing is not warranted. In these cases, however, vector processing still provides valuable quantitative validation of the natural-separation assumption.

Key words: multi-component seismic, vector processing, P/S wavefield separation

INTRODUCTION

Multi-component seismology captures both the horizontal and vertical components of ground motion. The resultant seismic record is a vector entity containing information on the particle motion of the propagating waves. This enables discrimination between compressional (P) and shear (S) wave arrivals. Current analysis of multi-component seismic data typically involves scalar processing of the vertical component to provide a conventional P-wave image, and scalar processing of the horizontal components to yield a converted-wave or P-S image. A number of convincing examples now exist where such multi-component seismic imaging has considerably enhanced exploration (e.g. Kendall et al, 1998; Barkved et al, 1999; MacLeod et al, 1999; Potters et al, 1999; Rognø, 1999).

While significant results have been achieved using appropriate component selection to produce P- and S-wave images, this conventional approach to processing multi-component data ignores the potential cross-contamination of P-wave energy on the horizontal components, and S-wave energy on the vertical component. Basic ray-parameter concepts (e.g. Aki and Richards, 1980) dictate that such contamination is more likely to be observed in vector seismic data acquired over areas exhibiting relatively high-velocity surface layers (e.g. areas with surface basalts and/or limestone reefs) rather than in seismic data collected over areas with low-velocity surface layers. Furthermore, for survey areas characterised by a relatively low surface-layer V_p/V_s (approximately less than 1.6), where V_p and V_s are the P- and S-wave velocities respectively, any such cross-contamination will be accentuated as a result of the incoming seismic wavefields interacting with the free-surface or ocean-bottom boundary. Cross-contamination of P- and S-wave energy has been observed in a number of seismic modelling exercises and multi-component case studies (e.g. Chen et al, 1999; Li and Yuan, 1999; Metcalfe, 2002). Where wavefield cross-contamination occurs, true vector-processing techniques that take advantage of the actual wavefield particle motion to distinguish between wave types, have the potential to enhance P- and S-wave imaging and so amplify the considerable success already achieved with conventional multi-component seismic exploration.

VECTOR PROCESSING

The earliest attempts to exploit particle-motion information for P/S wavefield separation evolved from analysis of earthquake records (Shimshoni and Smith, 1964). Generally, vector-processing schemes derived from earthquake seismology use data from a single receiver station and involve polarisation analysis and filtering. Fundamental concepts and basic methodology associated with these single-trace vector-processing techniques are discussed further in Hendrick and Hearn (1999) and Hearn and Hendrick (1999). Note however, that the polarisation-filtering techniques borrowed from earthquake seismology are typically not suitable for P/S separation in exploration applications where P and S reflections often interfere with each other.

Successful extraction of P- and S-wave records from surface reflection data can be achieved if vector-processing schemes are extended to also take advantage of other, traditionally exploited signal properties, such as frequency and/or slowness. Over the past decade or so a variety of such multi-trace, multi-component wavefield separation schemes have been described. These range from vector techniques that operate in the *f-k* or τ-*p* domain (e.g. Dankbaar, 1985; Greenhalgh et al, 1990; Donati and Stewart, 1996), to methods that utilise the mathematical divergence and curl operators (e.g. Dellinger and Etgen, 1990; Sun, 1999), to separation schemes that are based on the frequency-domain parametric equations (e.g. Leaney, 1990; Cho, 1991; Richwalski, 2000). Amongst this sample of vector separation schemes, the parametric methods have, to date, received very little attention with respect to multi-component seismic exploration applications.

PARAMETRIC TECHNIQUES FOR VECTOR WAVEFIELD SEPARATION

We have specifically considered three frequency-domain parametric vector separation schemes, here referred to as: (i) Multiple Signal Classification (MUSIC) (Schmidt, 1981); (ii) Integrated Wavefield Separation (IWSA) (Cho, 1991; Richwalski, 2000); and (iii) Parametric Inverse Modelling (PIM) (Leaney, 1990).

The parametric data model that underpins each of these separation schemes is formulated by modelling each wavefield by its Fourier components and two frequency-independent parameters, namely slowness and particle motion. Cho (1991) and Richwalski (2000) provide a comprehensive derivation of this frequency-domain parametric model.

Further details on the MUSIC, IWSA and PIM vector methods are given in Hendrick (2001). The difference between MUSIC, IWSA and PIM relates to the method of recovery of the frequency-independent wavefield parameters. In brief, MUSIC utilises the frequency-domain covariance matrix (or spectral matrix) to define a signal vector-subspace, and then scans for slowness and polarisation parameters that will place the individual waves in the same vector-subspace. IWSA recovers wavefield slowness and polarisation through eigenanalysis of a transfer matrix that relates the Fourier spectra of data at one receiver to those at an adjacent receiver. PIM solves for the desired wavefield parameters using a non-linear inversion scheme that minimises error between the observed seismic data and the modelled data. For reasons of operational robustness and computational time, PIM is our preferred parametric-vector method. Once slowness and polarisation of the desired wave types have been determined, the three methods perform wavefield separation by substituting the slowness and particle-motion information for each wave type into the parametric equations and solving for the separate wavefields in a least-squares sense.

Theoretically each of these vector methods can recover parameters for any number of different wave types. However, in practice, the best results are achieved by considering only one or two of the more dominant wavefields at a time. As each wave type is successfully separated, it can be projected back into the vertical and inline directions and stripped from the original dataset to create a new input dataset containing fewer wave types. We refer to this process as iterative wavefield separation.

Note that the frequency-domain parametric model used for MUSIC, IWSA and PIM assumes that the vector wavefield is the sum of a finite number of plane waves, each characterised by constant slowness and polarisation. Consequently, these vector schemes must operate over limited trace and time windows to avoid variations in wavefield parameters.

The simple two-component synthetic shown in Figure 1 is used to demonstrate vector wavefield separation via PIM. This dataset contains a primary P reflection wavefield (three P-wave reflection events with zero offset times of approximately 0.47 s, 0.92s and 1.3 s), a primary P-S reflection wavefield, where conversion is assumed to occur at the deepest reflection point of the wave (three P-S reflection events with zero offset times of approximately 0.63 s, 1.24 s and 1.77 s), and a number of secondary P-P-S and P-S-P converted wavefields. There is significant cross-contamination of P energy on to the inline component, and S energy on to the vertical component. Separation of the primary P and P-S reflection wavefields from this dataset using traditional velocity-filtering methods (e.g. *f-k*) would not be entirely effective. First, the apparent velocities of these wavefields are not sufficiently distinct to permit *f-k* discrimination of the wavefields on each component, particularly on the near-offset traces. Secondly, even if the P and P-S reflection wavefields could be recovered from each component of data, there is no way of combining the vertical and inline P-wavefield components (or P-S wavefield components) without incorporating particle-motion information.

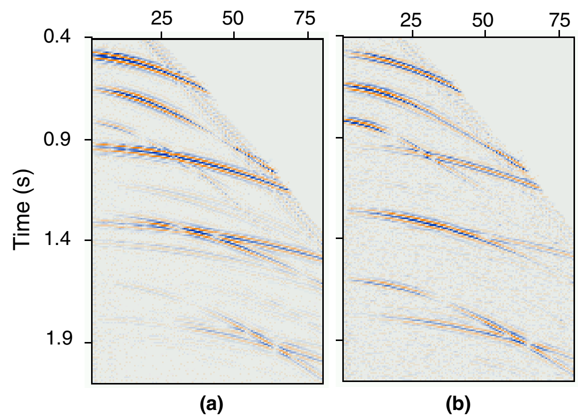

Figure 1. Two-component synthetic dataset: (a) vertical component, and (b) inline component. Trace spacing is 30m. Signal bandwidth is 12-90Hz. True relative amplitudes are shown.

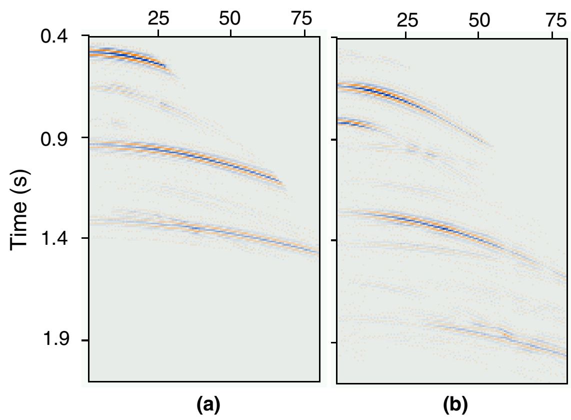

Figure 2. Wavefields recovered from synthetic data shown in Figure 1 via PIM: (a) P wave, and (b) P-S wave. Initial parameter estimates for PIM were recovered directly from the seismic data and single-trace polarisation analysis. True relative amplitudes are shown.

Figure 2 demonstrates the application of PIM to the vector data given in Figure 1. PIM has successfully extracted relatively pure P and P-S wavefields. Note however, that the P-S wave (Figure 2(b)) contains some weak P-P-S energy in addition to the primary P-S reflection wavefield. These two wave types have comparable slowness and polarisation so that vector processing cannot easily distinguish the wave types.

REAL DATA EXAMPLE - OBC

To demonstrate real-data vector wavefield separation, PIM is used here to recover P and converted P-S reflection energy from ocean-bottom cable (OBC) data. The vertical and inline components of the common receiver gather under consideration are shown in Figures 3(a) and 3(b). No pre-processing has been applied to these data.

As is typical of seismic exploration data, the recorded signal is a complex mixture of P and S body waves, and coherent and random noise. For these OBC data a significant portion of the recorded noise exists on the inline component, making detection of P-S reflection energy quite difficult. Nevertheless, there is some evidence of P-S reflection packages in Figure 3(b) (e.g. reflection events with near-offset times of 1.3 s and 2.3 s). In contrast, the vertical component (Figure 3(a)) shows several strong bands of P-wave reflection energy (e.g. reflection events with near-offset times of approximately 1.1-1.5 s and 2.0-2.3 s).

The OBC vector separation results achieved via PIM are given in Figures 3(c) and 3(d). Recall that the parametric vector methods assume constant wavefield slowness and polarisation within the data window being analysed. Thus, for these OBC data, the running window has been limited to seven traces. In addition, approximate P and P-SV NMO corrections have been applied prior to vector separation. This ensures that all events of a particular wave type are presented to the PIM algorithm with a consistent slowness. Application of NMO helps to maximise the time-length of the data that can be considered at any one time by PIM. The iterative approach to separation has also been used to assist with wave recovery in the presence of noise.

The P and P-S wavefields shown in Figures 3(c) and 3(d) can be projected back in to the vertical and inline directions to demonstrate that there is very weak cross-contamination of P energy on the horizontal component, and P-S energy on the vertical component. In terms of seismic imaging, this cross-contamination is negligible, and vector processing of these particular OBC data is unlikely to produce significantly cleaner seismic sections than those generated via conventional multi-component processing. Note however, that vector-processing has provided a qualitative validation of the natural-separation assumption.

CONCLUSIONS

Considerable success in a variety of exploration environments has been achieved using pseudo P- and S-wave sections produced via scalar processing of the vertical and horizontal components of multi-component data. True vector-processing schemes that exploit the particle-motion information inherent in multi-component data will produce more accurate P- and S-wave images where there is significant cross-contamination of the P and S energy on to the horizontal and vertical components, respectively. Where cross-contamination is less problematic, vector processing provides a qualitative tool for validating the natural-separation assumptions made for conventional multi-component processing, giving confidence to subsequent processing and interpretation of any pseudo P- and S-wave sections.

The ultimate vector processing tool for exploration-scale data combines frequency and slowness information with particle-motion information. MUSIC, IWSA and PIM are three such multi-trace vector methods, based on the frequency-domain parametric model of seismic data. PIM is the more robust and efficient of the parametric techniques. Practical implementation of the vector-separation techniques requires use of rolling-trace windows of limited time-length. Where more than one or two wavefields dominate the seismic record, optimum wavefield recovery can be achieved using an iterative approach to separation.

The high degree of interactivity required to select suitable analysis windows, design iterative wavefield separation and provide initial parameter estimates means that implementation of the parametric-vector methods in a highly-automated production environment is not yet viable. Rather parametric wavefield separation is more suited for use as a specialised multi-component processing validation tool and/or for vector processing over an already identified target horizon. Experience gained in such specialised studies will hasten the application of vector processing as a mainstream multi-component tool.

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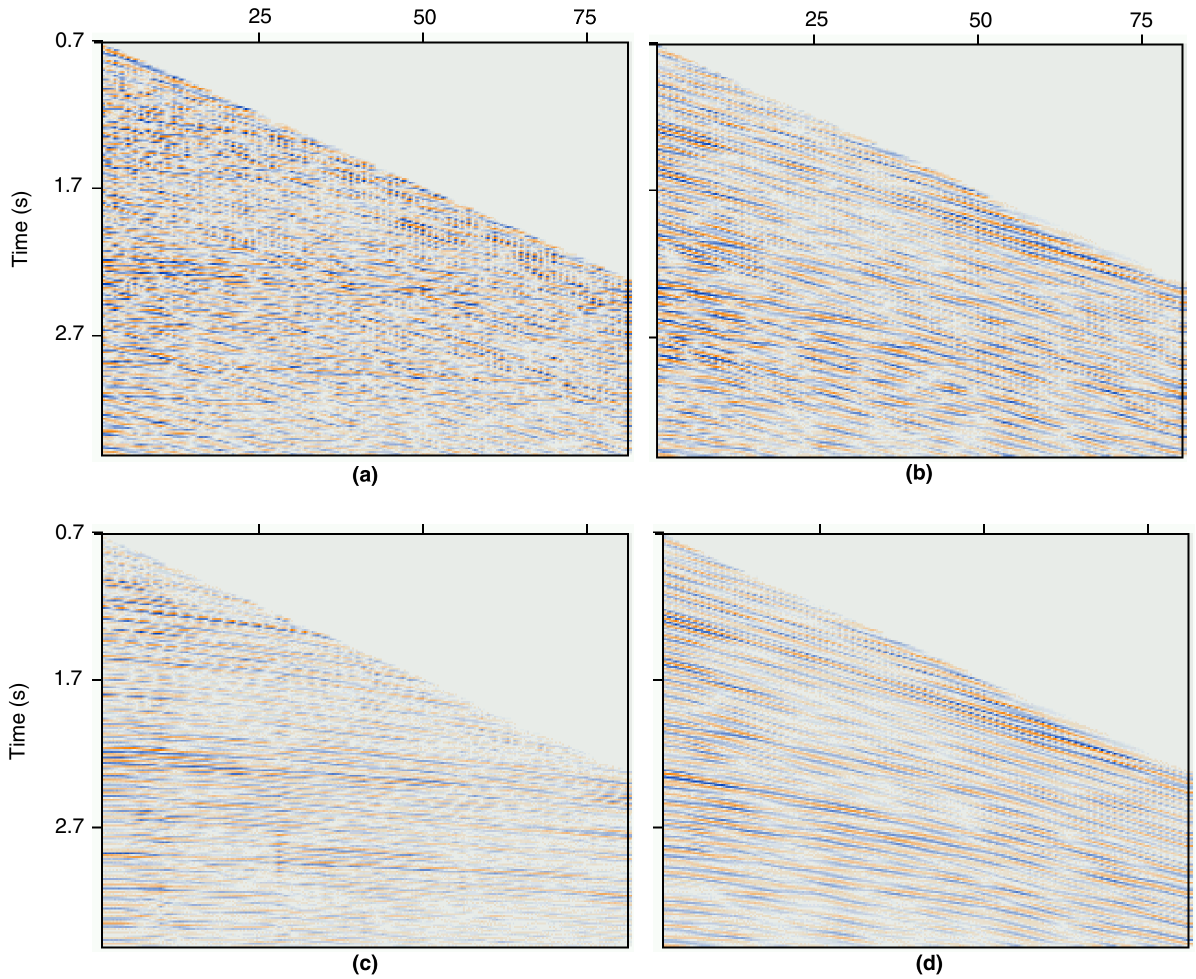

Figure 3. Vector wavefield separation for an OBC common receiver gather: (a) vertical component, (b) inline component, (c) P wave recovered via PIM, and (d) P-S wave recovered via PIM. The shot interval is 25 m, with source-receiver offsets here ranging from 693 m to 2668 m. The sample interval is 2 ms.