Ultra High Productivity Vibroseis Acquisition and Deblending Techniques
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Summary
Ultra high productivity(UHP) vibroseis acquisition is an effective method for reducing the cost of high-density land seismic exploration. BGP has successfully carried out the first UHP industrialized production in the world for Petroleum Development Oman(PDO) company. In this paper, the basic principle and acquisition challenges of UHP are introduced, and the technical solutions developed by BGP are summarized. Seismic data acquired by UHP has high blending fold, which poses great challenges for the subsequent separation algorithm. We have proposed a robust data separation method applied on 3D common receiver gathers, this method is parameterized in the frequency-wave number-wave number(FKK) domain, and it separates signal and noise by sparse inversion. Tests on synthetic and field data show that the proposed method is well suited for UHP data separation.

Introduction
Driven by the increasing demands to high density seismic data and the intention to reduce unit cost of seismic exploration, petroleum companies are keen on improving the productivity of seismic acquisition. In the past few years, there have been rapid developments of high efficiency vibroseis acquisition techniques. Slip sweep acquisition, distance separated slip sweep (DS3) and dynamic slip sweep technologies have been devised and widely applied in the Middle East and North African (Rozemond,1996; Bouska,2008). BP has developed Independent Simultaneous Sweeping (ISS) technique in 2006 and fully applied it in Libya by acquiring 13000 km² 3D land seismic project in 2008 (Howe,D., Foster,M., 2008,2009).

PDO proposed a new acquisition method called ultrahigh productivity(UHP) technique and has completed four field trials successfully from 2015 to 2017. In September 2017, UHP was officially put into production. The fundamental of UHP acquisition is based on Time-Distance rules(TD, see Figure 1), which states that multi group vibrators shoot independently with minimal constraints in continuous recording mode of the cable recording system. Seismic waves from different vibrator points (VPs) in a time segment are continuously recorded in a mother record of a fixed length. The advantages of UHP are that field acquisition time and acquired seismic data size have been reduced significantly. However, it leads to the blending and unwanted interference of seismic waves from different simultaneously sweeping VPs. Therefore, the signal and noise separation is necessary for UHP data processing.

Blended data separation methods can be divided into two categories: denoising methods and inversion methods. The denoising methods exploit the random characteristics of interference noise in certain type of gathers. Huo et al. (2009) introduced a vector median filter to suppress interference noise in common midpoint domain. Wang et al. (2014) proposed a method to better preserve primary source energy using alpha-trimmed vector median filter. Mahdad et al. (2011) introduced an iterative algorithm using f-k filtering in common receiver gathers. Zhou et al. (2016) applied an adaptive multi-level median filtering to blended marine data, which iteratively extracts primary wave field details by reducing the median filter window. However, when blending fold is high, denoising methods can damage signals, and result in poor data separation.

The inversion methods exploit sparsity of the signal in certain transform domain, which first extract signals step by step through shrinking thresholds, and then remove the interference noise predicted by the signal to further improve separation result. Chen et al. (2014) proposed a deblending algorithm using shaping regularization in seislet domain. Zuetal.(2015) introduced an inversion scheme in curve let domain, and improved separation using a periodically varying code in marine acquisition. Compared with the denoising methods, the inversion methods can better separate blended data, but the computing cost is very high, especially for data with high blending fold, low signal to noise ratio and large data volume, which poses great challenges for data separation.

In this paper, an inversion-based separation method applied on 3D common receiver gathers is proposed. This method usesL0 norm constraint in the FKK domain and separates signal and noise iteratively. In this method, fast Fourier transform is used to improve the computational efficiency, and convergence speed is accelerated by a shrinking
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threshold function, by which highly-blended seismic data can be separated in an accurate, stable and fast way.

UHP Technique Acquisition Challenges and Solutions

Main challenges for UHP acquisition are listed below:

**Challenge1:** During UHP acquisition, each vibrator scatters along the swath (Figure 2) to reduce the impact of TD rules. However, the instrument (cable system) adopts micro-seismic mode to continuously record the data, it cannot realize job management and assignment distribution in real time.

**Challenge2:** During UHP operation, recording instrument cannot monitor the spread (abnormal trace, line fault) and guide field operation, and will not realize blended data quality control and vibrator status monitoring.

**Challenge3:** Ensure the retrieval rate of ground force files is not less than 98.5% as client required.

**Challenge4:** UHP indoor QC and SPS generation.

**Challenge5:** UHP blended data indoor QC and on-site processing.

BGP has integrated its Digital-Seis System (DSS), KLSeis software, GeoEast with the technology and developed the associated software packages for vibrator operation management with QA/QC.

**Solution 1:** Utilize DSS to monitor vibrator attributes, manage field operation and job assignment.

The crew can monitor the locations and shooting conditions of each shot in real time by DSS (Figure 3); Digital-Seis Commander (DSC) is used to display the vibrator’s attributes of the current shot or the average vibrator attributes of the latest VPs in a histogram; DSC can also arrange and adjust assignments of the vibrators by user-defined parameters.

**Solution2:** Use KL-RtQC software to identify abnormal channels and send the information to DSC.

KL-RtQC software can analyze and identify abnormal channels, verify acquisition parameters, analyze energy abnormal and other attributes of records (Figure 4). It can identify abnormal channels and validate records based on analysis on mother record, and send results to DSC via network protocol in real time.

**Solution3:** Retrieve, monitor and remote copy the ground force files.

Monitor the ground force by Digital-Seis Guidance (DSG). If ground force files are lost consecutively, it will alarm the drivers to stop production and inform the mechanics to ensure that the retrieval rate of the ground force files is greater than 98.5%.

For the purpose of downloading the ground force files in an efficient way, the crew added the function of remote copy to the software, which has the ability to retrieve the ground force files within 30 meters of the vibrators.

**Solution4:** Use KLSeis for indoor support document QC.
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SPS file is compiled based on field returned information such as TB time, latitude and longitude coordinates in ground force files. And data blending level is monitored and analyzed using developed software. Attribute statistics and analysis (Figure 5), such as elevation, TD rules and vibrator attributes, is realized for quality control.

Solution 5: Develop onsite UHP processing module in the GeoEast system.

UHP CorrSeparation module in GeoEast can merge, correlate and cut the UHP data efficiently. The processing efficiency can be enhanced by selecting multi-node parallel processing mode. Figure 6 shows a typical field onsite processing flow and CDP line stack profile respectively. And the data imaging quality is favorable.

Data Separation by Sparse Inversion

In blended acquisition, the multi-source records measured by each receiver can be expressed as:

\[ d = \Gamma m \]  

where \( d \) denotes blended data, \( m \) denotes signal model in a common receiver gather, \( \Gamma \) is a blending operator which describes excitation time and position information of all sources. While blended data and the blending operator is known, the problem of solving the signal model directly by Equation 1 is ill-posed. Because number of time samples in the blended data is much less than that of the signal model. In order to obtain a unique solution, additional constraints need to be imposed on the unknown signal model.

Coherency difference between signal and interference noise in time-space domain common receiver gathers can be characterized by sparsity in the FKK domain. Therefore, we propose to impose L0 norm constraint on the signal model in FKK domain, and establish the objective function as:

\[ J(m) = \frac{1}{2} \| d - \Gamma m \|_2^2 + \lambda \| Fm \|_0 \]  

where \( F \) denotes three-dimensional fast Fourier transform, \( \lambda \) is the regularization parameter that controls the weight of error term and constraint term. This objective function minimization problem can be solved by iterative shrinkage threshold method:

\[ \Gamma^{-1} F^T F \left[ (I) \right] \Gamma^{-1} d \]

where \( \Gamma^{-1} \) denotes the conjugate transpose of the blending operator, \( \Gamma^{-1} d \) is the least squares solution of equation 1, i.e. the pseudo-separated common receiver gather, \( (\Gamma^{-1} \Gamma - I)m_i \) represents interference noise predicted by the estimated signal, initial signal model is typically set to zero. \( \Gamma^{-1} \) Denotes inverse Fourier transform operator, and \( T \) is the thresholding operator in transform domain. In this paper, a hard thresholding function is adopted to set data with amplitude greater than given threshold to zero:

\[ T[ f(m) ] = \begin{cases} f(m), & |f(m)| \geq \tau \\ 0, & |f(m)| < \tau \end{cases} \]  

Where \( f(m) \) denotes FKK domain data. In order to speed up convergence rate, the exponential threshold shrinkage function is used.

Figure 7 illustrates the basic steps of our proposed method with a flow chart:

1) Pseudo-separate the blended data \( \Gamma^{-1} d \).
2) Calculate the maximum amplitude of the pseudo-separated data in FKK domain, and determine the threshold shrinkage function.
3) Predict interference noise from initial (or updated) signal model \((\Gamma^d \Gamma - I)m_G\).
4) Subtract noise from pseudo-separated data to update the signal model \(\Gamma^d d - (\Gamma^d \Gamma - I)m_G\).
5) Apply thresholding process to the signal model in FKK domain using \(F^TF\Gamma d - (F^T \Gamma - I)m_G\).
6) Repeat step 3) to step 5), until the maximum number of iterations is reached, obtains fully separated signal and noise.

Figure 7 Flowchart for deblending algorithm in FKK domain

Examples

The proposed method is tested on both 3D synthetic data and field data with high blending fold.

Synthetic data application

The synthetic data simulate the seismic data acquired with 10 sources shooting simultaneously. Figure 8a shows pseudo-separated 3D common receiver gather. The blended noises are strong due to high blending fold, and appear as pseudo-random spikes. Three consecutive events are signals, the waveform of the signals is distorted due to the interference of noise, and the weak signals at deep parts are smeared by noise. It is very difficult to separate the data. Figure 8b shows the separated signals using the proposed method after 20 iterations, blended noises are completely removed and the weak signals are well recovered. There are almost no signal leakage can be visually observed in the separated noise shown in Figure 8c.

Figure 9 shows the separation results on source gathers. The strong interference source energy in pseudo-separated source gather (Figure 9a) have been accurately removed using our proposed method (as shown in Figure 9b), and the weak signals between 1500 ms and 2000 ms are well preserved, no primary source energy leakage can be observed in the separated interference noise (Figure 9c), which proves that our method can protect signals while eliminating noise.

Figure 8 Synthetic data separation results on common receiver gathers.
   a) Raw data, b) Separated signal, c) Separated noise.
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Figure 9 Synthetic data separation results on common source gathers.
   a) Raw data, b) Separated signal, c) Separated noise.

Real data application

The proposed method is further tested on a field blended 3D data. Figure 10a shows a pseudo-separated common receiver gather, blended noise spread throughout the profile. The separated primary sources’ data after 30 iterations with our proposed method is shown in Figure 10b, the signal-to-noise ratio of the common receiver gather data is significantly improved and the weak signal is well preserved. Figure 10c shows separated noises. It is clear that the signals and noises have been completely separated, and our proposed method can distinguish between the signal and noise very well.

Figure 10 Field data separation results on common receiver gathers.
   a) Raw data, b) Separated signal, c) Separated noise.

Figure 11 shows separation results on common source gathers. The pseudo-separated source gathers (Figure 11a) include seismic waves from at least 8 sources, distances between simultaneous sources are small along the cross line direction. It is very difficult to separate blended data. However, there are almost no interference noise leakages in the separated primary source’s data shown in Figure 11b, continuity of seismic events are strengthened and weak signals before strong event are well preserved. It is worth noting that no signal leakage can be observed in the separated interference source gather (Figure 11c), which supports the fidelity of the method. Figure 12 shows the separation results on stack section, the weak reflections from deep layers are recovered very well.

Figure 11 shows separation results on common source gathers. The pseudo-separated source gathers (Figure 11a) include seismic waves from at least 8 sources, distances between simultaneous sources are small along the cross line direction. It is very difficult to separate blended data. However, there are almost no interference noise leakages in the separated primary source’s data shown in Figure 11b, continuity of seismic events are strengthened and weak signals before strong event are well preserved. It is worth noting that no signal leakage can be observed in the separated interference source gather (Figure 11c), which supports the fidelity of the method. Figure 12 shows the separation results on stack section, the weak reflections from deep layers are recovered very well.

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Figure 12 Field data separation results on common receiver gathers.
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Figure 11 Field data separation results on common source gathers. 
a) Raw data, b) Separated signal, c) Separated noise.

Figure 12 Field data separation results on stack section. 
a) Raw stack, b) Separated signal, c) Separated noise.

Conclusions
The innovation of utilizing cable systems with vibrators shooting independently based on TD rules has proven to be reliable and effective. The UHP technology immensely improves efficiency and greatly reduces the costs of seismic exploration. BGP developed a complete set of technical package that can ensure UHP acquisition to be fully implemented. An accurate, stable and fast deblending method is proposed. This method separates signal and noise by sparse inversion in the FKK domain. Synthetic and field data applications have verified its effectiveness in separating seismic data with high blending fold. Moreover, due to the use of exponential thresholding and fast Fourier transform, the method has fast convergence speed and high computing efficiency, which makes it well-suited for practical applications.

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