Investigating Different Approaches of Deblending Seismic Data

by

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Abstract

Shooting in an overlapping fashion is called blended or simultaneous acquisition. This can make acquisition efficient and economical. However, deblending (i.e. the process of separating the blended data) of data can be challenging.

Blended seismic data can be acquired in a number of different configurations. Examples are a shooting vessel follows the tail buoy of a conventional streamer vessel or a shooting vessel and conventional vessel are parallel. One can also vary the signal strengths and frequency bands of the sources for the two vessels. In this way both shallow and deep resolution can be improved as low frequency waves penetrate deep as compared to high frequency waves.

In this thesis I have tried various conventional seismic processing techniques (like tau-p transformation, FK filtering, SVDMUL, Time-frequency Denoising, and FX prediction) to deblend or separate the blended data. I used several datasets (one real and 2 synthetic), with different geometries, but all the datasets have same acquisition design in which one vessel is in front of the streamer and the other is behind the streamer cable.

I tried to separate or deblend the data either on the bases of their dips, or alternatively by transforming the deblending task into that of denoising. Events related to the shooting vessel appear as random noise in Common depth (CDP), common receiver (CR) and Common offset domain (CO). SVDMUL and TFDN methods are then applied in the CO and CDP domains respectively.

I found that the best deblending results were obtained using SVDMUL (Singular-value decomposition approach) for all data sets. SVDMUL is used iteratively and the deblended result is gradually built up. This method performed superior compared with deblending based on TFDN, FK or tau-p coherency filtering. The tau-p transformation based method showed significant problems in areas of strong or conflicting dips. The efficiency of TFDN and SVDMUL methods are based on the time jitter between the shots from to the conventional vessel and shooting vessel. If too small the techniques from worse.
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1 Introduction

Major work of this thesis was carried out at Fugro Seismic Imaging (FSI) Oslo-Norway. The main objective of this thesis is to identify the possible ways of decomposing the blended seismic data in its separate source parts by using conventional seismic processing techniques.

1.1 The aim of the thesis

Blended seismic acquisition is a new chapter in seismic acquisition and it has been a source of attention from some time. Potential benefits of using more than one source at the same time includes the acquisition of relatively larger amount of data in less time as compared to the conventional acquisition time along with more freedom in azimuthal coverage.

Deblending is the procedure of recovering the data as if they were acquired in a conventional, unblended way. Different processing techniques have been proposed by many authors to deblend such data. The main motivation of this thesis is to establish various ways to deblend the data which are efficient and less time consuming as compared to the previously proposed procedures, employing conventional processing techniques.
2 What is blended data?

Shooting in an overlapping fashion is called blended or simultaneous acquisition. Simultaneous source firing has the potential of causing a major cost reduction in seismic data (Beasley, 2008).

Traditionally a seismic survey is conducted in such a way that the time interval between shots is large enough to avoid overlapping. But in blended acquisition records do overlap leading to much wider and denser geometries in an economic way (Guus, Gerrit and Eric, 2010).

In blended marine acquisition two or more sources are ignited with random delay in time. Although the recorded data are blended, conventional processing procedures could still give acceptable results (deblending), (Shoudong, Yi and Panos, 2009).

2.1 What we do in blending

Simultaneous source firing is common for vibroseis acquisition where signal coding is applied. But this type of signal coding is not possible for air gun arrays used in marine seismic. In this case sources fired with random delays at different locations give the solution to this problem.

Source blending is continuous signal recording of multiple sources and recorded data overlap in time. The properties of multiple sources (that provide the base line to distinguish the signal) are the locations (azimuth and offsets) and their time shifts. Signal signature can also be used if on land.

Detector blending is continuous recording of the signal, recorded by multi detector configurations. The multidetector properties (that provide the base line to distinguish the signal) are the location of the detectors and their time shifts (Gerrit, Guus and Eric, 2009)

2.2 Why we do it

The Cost of a 3D marine seismic survey is always an important issue. Flip flop shooting used in marine streamer surveys actually doubles the production rate, but time sharing between sources
results in decreased fold. In the flip flop geometry, the fundamental assumption is that only one source can be active for a given seismic record, that imposes an upper limit for source efficiency. If two or more sources are active simultaneously, it increases the acquisition efficiency. This increased efficiency can be categorized in the following ways:

**Cheaper** - The quality of the survey e.g. S/N and illumination can be achieved by using multiple sources with less cost so it is more economic than conventional acquisition. As more than one source is ignited at the same time, this increases the production rate which ultimately leads to a significant reduction in cost of the survey.

**Better quality** - This type of acquisition provides better quality data due to freedom in large offsets and wide azimuth (Beasley, 2008). Wider aperture /or denser shot sampling makes each subsurface point illuminated from a larger number of angles that results in an improved image.

Another aspect of simultaneous acquisition is that multiples (secondary wave fields) are also considered in the subsurface illumination. Multiples illuminate the subsurface grid point from different angles than primaries that eventually gives better resolution and S/N.

### 2.3 Drawbacks

One major drawback in blended acquisition is the presence of crosstalk noise, due to the nearly simultaneous firing of the air gun arrays. It is important to understand the characteristics of this noise and adapt proper processing workflows and techniques to remove or reduce its effects on image quality.

Further we more need to put some extra processing effort into deblending the data. Thus during acquisition one should make sure that data should not be mixed or blended to an extent so that during deblending decomposed images of good quality cannot be obtained.

Most of the deblending techniques rely on the fact that cross talk noise appear coherently in shot domain and randomly when viewed in a different domain like common depth (CDP) domain.
In this thesis several approaches to deblending have been investigated.

2.4 Ways of acquiring blended data

Normally we need at least one extra shooting vessel to acquire blended data. Below we discuss possible geometries for blended shooting.

A) Normal blended acquisition

![Setup A of blended acquisition](after Peter et al., 2009)

**Description**

The idea is that one shooting vessel follows the tail-buoy of the conventional streamer vessel. Both vessels fire their guns almost simultaneously, but with random delay applied in the range of [4, 500ms].

Because of the sampling rate, the delays should be in multiples of 4ms. Example of a sequence could be [140, 16, 324, 496, 32 …]. The sequence needs to be several hundred numbers long before it repeats. The simultaneous shooting method has been described in Vaage, 2002 (patent by PGS, Americas INC).

The main risk in this operation is related to the source vessel following close behind the tail-buoy of the seismic steamer vessel. If there was a loss of propulsion on the seismic vessel, the source vessel must be careful not to get into the tail-buoys – or the streamers.
This acquisition gives two sets of data simultaneously where the CMP swath is illuminated from both sides with an 180° difference in azimuth.

B) Single vessel blended acquisition

![Diagram of blended acquisition](image)

*Figure 2.2: (a) Setup B of blended acquisition. (b) Midpoint chart illumination by using setup B of blended acquisition (stratigraphic assumption), (after Peter et al., 2009).*

**Description**

The idea is to use one shooting vessel in parallel to the seismic vessel. Both vessels fire their guns almost simultaneously but keeping some random delay in the range of 4 to 500 ms at the shooting vessel side. Here we obtain two CMP swaths thus the amount of data is doubled.

The distance between the two vessels needs to be chosen so that the CMP swaths are next to each other. For example in case of a 10-streamer seismic vessel with a 100m streamer separation, the shooting vessel separation needs to be 1000m.

For both the above mentioned methods (A and B) the amount of data is doubled with little additional cost of the survey. For example, a conventional seismic vessel costs generally 250 thousand USD per day and a shooting vessel costs typically 50 to 100 thousand USD per day. So the total cost of the survey is increased from 250 thousand USD to 350 thousand USD but the amount of data is doubled.
C) **Blended acquisition (BA) with super-long offset**

![Diagram of Setup C of blended acquisition](image)

*Figure 2.3: Setup C of blended acquisition. (Fugro internal report, 2010)*

**Description**

The idea is that we use two seismic vessels both fired almost simultaneously, but keeping some random delay for one vessel. In this way we obtain a super long offset recording that provides very deep investigation. This method is not as economic as the above mentioned methods A and B.
D) **Blended acquisition with both shallow and deep resolution**

![Diagram of blended acquisition](image)

*Figure 2.4: Setup D of blended acquisition. (Fugro internal report, 2011).*

**Description**

The idea is that one shooting seismic vessel follows the tail-buoy of the streamer vessel (conventional seismic vessel). But the signal strengths and frequency bands are different for the two vessels. In this way one can improve both shallow and deep resolution as low frequency waves penetrate deep as compared to high frequency waves ([cf. Fig.2.5](#)) ([Rommel, Elboth, 2011](#)).
Figure 2.5: Setup D of blended acquisition showing area of better resolution. (Rommel, Elboth, 2011).

This idea is from discussion with my supervisor.
3 Review of proposed deblending techniques

Several authors have discussed the idea of simultaneous and nearly simultaneous source shooting. Barbier (1974) suggested that more than one source can be used in seismic acquisition. These sources emit energy with same amplitudes and are laterally offset each other. The distance between the sources is same as the distance between the receivers. The time interval between the consecutive sources is a multiple of one basic time unit plus a fixed time unit. The sequence of multipliers form a series of random numbers. Silverman (1979) proposed the use of simultaneous vibrators transmitting the same or different reference signals. Beasley et al. (1998) and Beasley (2008) proposed that marine seismic data can be acquired by means of simultaneous impulsive sources with large spacing between the illuminating shots. Vaage (2002) proposed the acquisition of marine seismic data with random, quasi random or synthetic delay times between the firing sources. The term source blending was first introduced by Berkhout (2008). Berkhout et al (2009) extended the concept of source blending to detector side by combining incoherent shooting with the incoherent sensing and thus gave the concept of double blending.

Fourier transformed seismic data (time to frequency) can be represented by a data matrix P as shown in Figure (3.1), (Berkhout, 1982). Each element of this matrix represents a complexed valued frequency component of a recorded trace. The arrangement of elements in this data matrix is in such a way that one row represents a common receiver gather and one column a common source gather and with corresponding diagonals representing common midpoint and common offset gathers.

![Figure 3.1: A schematic representation of data matrix.](image_url)
Mathematically the data matrix \( P \) can be represented by the following expression (monochromatic case):

\[
P(Z_d, Z_s) = D(Z_d) X(Z_d, Z_s) S(Z_s)
\]

where \( Z_d \) and \( Z_s \) are respectively detector and source depth, and \( D \) represents the detector matrix, \( S \) is the source matrix and \( X \) is the multidimensional transfer function of the Earth which includes all primaries as well as multiples and wave conversions.

The data matrix \( P \) in equation (3.1) can only sample \( X \) well if the acquisition geometry is well designed and source and detectors are well sampled.

Continuous recording of sources, fired simultaneously but encoded incoherently is what we call source blending. Source blending is similar to plane wave synthesis and controlled source illumination as in both cases multiple sources are fired simultaneously (Rietveld and Berkhout, 1994) but it differs from the latter ones since they generate continuous (coherent) wave fronts. In source blending such wave fronts are not desired because they may introduce special band limitations at every subsurface point. An extended temporal and spatial bandwidth can be obtained if every point in the subsurface is illuminated by an incoherent or white signal (within a certain bandwidth).

Mathematically source blending can be represented by the following expression;

\[
P'(Z_d, Z_s) = P(Z_d, Z_s) G = D(Z_d) X(Z_d, Z_s) S(Z_s) G
\]

where \( P' \) is the blended data matrix and \( G \) is the blending or Green’s function matrix containing the blending parameters. Columns of this latter matrix represent areal sources (combinations of point sources) and each element represents phase or amplitude encoding.

To deblend data from areal to individual shots a matrix inversion has to be performed on the Green’s function or blending matrix. When this inverted matrix is multiplied with the blended data matrix \( P' \) then the result will be a deblended data matrix.

As the number of columns of the blended data matrix (known data matrix) is less than the deblended data matrix (unknown data matrix) this is an underdetermined inverse problem and
the true inverse of \( G \) does not exist (as \( G \) will not be a square matrix in this case). Thus the best way to solve this inverse problem is to find a least-squares solution.

The least square inverse of the Green’s function matrix \( G \) can be found from the following expression:

\[
< G^{-1} (Z_d, Z_s) >= (G^T G)^{-1} G^T
\]  
(3.3)

where \( T \) means transpose.

This least-squares solution can be further simplified if the source codes are phases. In that case the inverse will be equivalent to the Hermetian of the Green’s function:

\[
< G^{-1} (Z_d, Z_s) >= G^H
\]  
(3.4)

where \( H \) means transpose and complex conjugating.

The inverse problem then reduces to:

\[
< P(Z_d, Z_s) > = P'(Z_d, Z_s) G^H
\]  
(3.5)

where \( < P(Z_d, Z_s) > \) is the pseudo deblended data matrix.

A main problem that may arise from this inverse solution is the generation of correlation noise or cross talk. As one column of the blended shot record consists of responses from multiple sources and the codes among these sources are not exactly orthogonal, the deblending procedure introduces some cross terms which are known as blending noise or correlation noise (Berkhout, Blacquiere and Verchhur, 2010).

Berkhout (2008) proposed two processing options. The first one is as discussed above applying a data driven inverse of the blending operator to the blended measurements (‘deblending’). This gives deblended data with a relatively high source density, which can be further used in standard seismic processing. The other option is to apply various processing techniques directly on the blended data. This may be a start of a new learning process in seismic processing.

Separation of blended data by iterative estimation and subtraction of interference noise was proposed by Mahdad et al (2010).
The separation process (deblending) was addressed as a blind signal separation problem by Ikelle, (2007). He used the independent component analysis as the tool to distinguish between the different blended sources. An inversion approach was proposed by Herrmann et al (2009), carrying out the data separation in the curvelet domain. Both the above mentioned approaches used sophisticated source codes as sweeps, random phase or amplitude encoding. Neelmani et al (2008) used forward modeling to deblend the simultaneous acquired data.

There is another interesting approach to deblend the data proposed in the literature. The main idea is to transform the deblending problem into that of denoising. The interference due to blending is then treated as noise. Several authors like Moore et al (2008) and Akerberg et al (2008) have proposed that by sorting the acquired blended data into different domains like the common receiver domain, common depth domain (CDP) or common offset domain, the interference noise appear as random events. Thus the deblending process converts into a typical random denoising problem. Based on this property conventional processing steps (that are used to remove the random noise) can be used to deblend the blended data. In the common receiver domain, the signals appear as coherent events whereas the interferences from the other source appear as random ‘spikes’. So any method that can distinguish between the coherent events and random ‘spikes’ up to some degree could be used to suppress the blending interference (Doulgeris et al., 2010).

Huo et al, (2009) used a vector median filter after resorting the data into the common midpoint domain. This 2D filter works locally and effectively reduces the amplitudes of the random ‘spikes’. Moore (2010) used an inversion approach in the radon domain to deblend the blended data.

Spitz et al (2008) suggested that a noise model can be build based on the velocity model using wave theory. The modeled interference noise is adaptively subtracted from the data. Kim et al (2009) moved a step further; they built a noise model from the data itself and then adaptively subtracted the modeled noise from the acquired data. The technique was applied in the common offset domain and was applied to OBC (Ocean bottom cable) data.

This thesis work is inspired and based on these previous attempts of deblending, i.e. a combination of data sorting in different domains and standard processing techniques.
4 Methods used to deblend the data

In this chapter we investigate different ways of deblending the data. Various methods are applied:

- FK Filtering
- Tau-p transformation and flirting
- TFDN (time frequency denoising)
- FX Prediction
- SVDMUL (Singular Value Decomposition)

These methods are used in different data domains. The basic idea is that we transform the deblending problem into that of denoising where any conventional seismic method can be used. TFDN is used in the CDP domain and SVDMUL in the common offset domain, as in these domains events related to the shooting vessel appear as random noise. Several authors like Moore et al., (2008) and Akerberg et al. (2008) have proposed to sort data in different domains as part of deblending.

4.1 FK Filtering

Seismic data is recorded in time domain, but several processing routines transform the data into some other domain, where the signal can be more easily separated from the noise by some filtering operation, and then transformed back to the original domain.

Thus filtering is used in seismic processing routines to alter the seismic data in such a way that its quality is improved by removing noise.

Fourier transformation is the most important transformation used in seismic. It states that a seismic signal can be decomposed into a sum of monochromatic signals (cosine functions) where each cosine function is characterized by its own amplitude, phase and frequency. By use of the Fourier transformation a seismic signal is transformed from time domain to frequency domain and its equivalent amplitude and phase spectra, (Gelius and Joansen, 2010).

FK transformation is a two dimensional Fourier transformation, where spatial coordinates are transformed to wave number domain (k) and time is transformed to frequency (f) domain.
The space dimension \((k)\) is controlled by the trace spacing and it is similar to the trace sampling in time domain, therefore it must be sampled according to the Nyquist frequency to avoid spatial aliasing (Excess Geophysics, www.xsgeo.com).

The FK transformation has the characteristics that a set of linear evens with the same dip gathers along one line in the FK-domain, (see figure 4.1).

![Figure 4.1: FK transformation of an ensemble of parallel and dipping lines gathers one dipping line (Gelius and Joansen, 2010).](image)

Synthetic data composed of two monochromatic plane waves having both different temporal frequency and dip (positive and negative, cf. Fig. 4.2a) will after FK transformation fall at two separate points in the FK spectrum (separation in frequency and dip) as shown in Figure 4.2 b.
Figure 4.2: (a) Two monochromatic plane waves having both different temporal frequency and dip (time domain). (b) After FK transformation they separate due to different dip and frequency.

If we remove one of the plane wave components corresponding to the red encircled area in the FK spectrum in Figure 4.2 b and then transform back to the time space domain, only the monochromatic plane wave corresponding to the negative dip is left as shown in Figure 4.3.

Figure 4.3: Monochromatic plane-wave event with negative dip.

Thus the FK transformation helped us to separate the different dipping events in an efficient manner (Ikelle and Amundsen, 2005).

Linear coherent noise such as diffractions and refractions can be more readily separated in the FK domain as compared to time-space domain, and hence can be muted away before the inverse transformation is applied (Excess Geophysics, www.xsgeo.com).
Spatial aliasing is a common problem in seismic processing and it is more visible in the FK domain as compared to the time domain.

![FK spectrum](image)

**Figure 4.4:** (a) Time domain. (b) Frequency domain.

In Fig. (4.4) the flat red event is transformed to a straight line at K=0 in the FK spectrum corresponding to zero dip. However the curved green event is mapped to a range of dips. The blue dipping refraction maps to a dipping blue event that becomes spatially aliased in the FK spectrum and being folded back (at broken line). One way of removing this aliasing is to filter all higher frequencies that cause aliasing but it will be harsh for the primaries too. The other way is to decrease the trace spacing as demonstrated in Fig. (4.5).

![Trace spacing](image)

**Figure 4.5:** (a) Trace spacing of 12.5m. (b) Trace spacing of 25m (spatially aliased).

Several authors have pointed out the use of FK filtering to separate or deblend data. Mahdad et. al., (2011) used FK filtering in an iterative way to deblend the seismic data.
However in this study FK filtering is not used iteratively.

This characteristic of the FK transformation to deblend the blended data is further investigated in Chapter 5.

4.2 Tau-p transformation and filtering

Tau-p transformation offers an alternative view of the seismic wave field characteristics. In the tau-p domain all the subsurface reflectors are illuminated by incident energy of a fixed ray parameter ‘p’ equivalent to plane wave illumination. The advantage of the tau-p transformation is that we can study different wave modes as a function of their corresponding slowness value. This often provides a good separation between different seismic waves like multiples and ground-roll (Donati and Martin, 1995).

A plane wave in the time domain is represented by a dip ‘p’ and an intercept ‘tau’, which maps to a point in the tau-p domain. Each hyperbolic event (in shot gathers) consists of a family of plane waves which maps to an ellipse in the tau-p domain as shown in Figs. 4.6 and 4.7 (Excess Geophysics, www.xsgeo.com)

![Diagram](image)

Figure 4.6: (a) Hyperbolic events in time domain (shot gather). (b) An ellipse in the tau-p domain corresponds to a hyperbolic event in the time domain.
The idea of using the tau-p transformation in this study is based on the observation that interference can be separated on the basis of different move out behavior (dip/or curvature value). After filtering of unwanted contributions data can be transformed back to time domain.

### 4.3 Time Frequency Denoising (TFDN)

Time frequency denoising is an efficient method to remove random noise, commonly used in standard processing. In TFDN, a window slides over the traces both in space and time. All the traces inside the window are transformed to frequency domain by using FFT (cf. Fig. 4.8). The amplitude estimate of each frequency is compared to the amplitude estimate of a presumably reliable trace segment (that is a threshold value defined by user) within the sliding window.
If the amplitude of any trace is larger than the threshold value, it is attenuated to the level of this threshold (cf. Fig. 4.9). The selection of threshold value is dependent on the noise contribution in the data. The threshold values used in TFDN are: Average (AVG), Median (MED), Lower quartile (LQT), Minimum (MIN) and Automatic (AUT) (Elboth et al., 2010).

**Figure 4.9: Illustration of how one frequency at a time is checked for noise. The red ellipse marks a gathering of amplitudes for one specific frequency. (Presterud, (2009)).**

In case of Median (MED), for each window position the amplitudes are calculated, sorted and then the median is computed as shown in Fig. 4.10.

**Figure 4.10: How amplitudes are sorted and the median is calculated, (a) before sorting (b) after sorting.**

The median (denoted by the purple value in Fig. 4.10 a) is expected to represent the amplitude of a noise free signal. If the central trace amplitude marked as green in Fig. 4.10 is larger than the median, it will be attenuated according to a user defined threshold value. Median is a good choice if less than 50% of the traces in the window are affected by noise. Similarly in case of Average (AVG) the average amplitude of all the traces inside the sliding window is calculated. If the central trace (green one in Fig. 4.10 a) inside this window is larger than the average value, it is attenuated. Average is not always a good choice as sometimes large amplitude of an anomalous single trace makes this value high. While in case of Lower Quartile (LQT), the lower quartile amplitude of all the traces inside the sliding window is calculated and this value is used
as a threshold. If the central trace (green one in Fig. 4.10 a) inside this window is larger than the threshold value, it is attenuated. It is a good choice if at least 25% of the traces are noise free. The Automatic (AUT) threshold value is calculated automatically based on the amplitudes of the traces inside the sliding window. If the central trace (green one in Fig. 4.10 a) inside the sliding window is larger than this threshold value, it is attenuated. This threshold value is useful in cases where the amplitudes of the traces are slightly above normal levels. For Minimum (MIN) threshold the minimum amplitude inside the sliding window is taken as the threshold value for TFDN. This is a very harsh threshold and must be used only if data are very noisy.

**Factor (FAC)**

The threshold value is supplied as a factor, its value ranges from 1 to 1000. By default its value is four. By decreasing this number it becomes more harsh to amplitudes. Factor allows the user to design different levels of threshold within a gather (Elboth et al., 2010).

TFDN is based on a user defined sliding window. It is therefore needed to provide information about the start and end times of the TFDN processing (in ms). The size of the sliding window in ms and its horizontal width (i.e. the number of traces inside the window) is defined by the user. The maximum and minimum frequency is also user defined. Fig. 4.11 summarizes the schematics of TFDN.
4.4 Singular Value Decomposition (SVDMUL)

The data (p) and null (0) space of a linear data problem can easily be found through a type of eigen-value decomposition of the data kernel called singular value decomposition (William Menke, 1984). Thus any N×M matrix can be written as the product of 3 matrices,

\[ G = U \Delta V^T \]  \hspace{1cm} (4.1)

where U is an N×N matrix of Eigen-vectors that span the data space s(d);

\[ U = \{u_1, u_2, u_3, \ldots, u_n\} \]  \hspace{1cm} (4.2)

These vectors are orthogonal to each other and can be chosen to be of unit length, so that

\[ UU^T = U^TU = I \]  \hspace{1cm} (4.3)

Likewise, V is an M×M matrix of Eigen-vectors that span the model parameter space S(m) as

\[ V = \{v_1, v_2, v_3, \ldots, v_M\} \]  \hspace{1cm} (4.4)

These vectors are also orthonormal vectors so that;

\[ VV^T = V^TV = I \]  \hspace{1cm} (4.5)
The matrix $\Delta$ is an $N \times M$ diagonal Eigen-value matrix, whose diagonal elements are non-negative and are called *singular values*.

Consider now the case with $N=4$ and $M=3$ as an example;

$$\Delta = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \\ 0 & 0 & 0 \end{bmatrix} \quad (4.6)$$

The singular values $\lambda_1, \lambda_2, \lambda_3$ ... are usually arranged in order of decreasing size, and some of them may be zero.

The $\Delta$ matrix is partitioned into a sub-matrix $\Delta p$ of ‘p’ non-zero singular values and additional zero matrices as

$$\Delta = \begin{bmatrix} \Delta p & 0 \\ 0 & 0 \end{bmatrix} \quad (4.7)$$

Where $\Delta p$ is a $p \times p$ diagonal matrix. The singular value decomposition then becomes:

$$G = UV^T = U_p \Delta_p V_p^T = \sum u'_p \lambda_p v'_p = \sum E_p \quad (4.8)$$

where $U_p$ and $V_p$ consist of the first ‘p’ columns of $U$ and $V$ respectively. The remaining parts of the Eigen-matrices define the null space (Leon, 2002). In Eq. (4.8) $E_p$ represents an eigen image corresponding to the eigen value $\lambda_p$.

We can apply this general concept of SVD to our case of simultaneous source data. If we sort our blended data in the common offset domain then the events associated with the front vessel will appear as coherent events, while the data associated with the shooting vessel will appear as random ‘spikes’.

By keeping only the Eigen images $E_p$ corresponding to the high eigen values, the coherent part of the data is preserved while the random noise is efficiently reduced (*cf.* Fig. 5.34b).
4.5 F-x Prediction

Random noise in seismic data can be attenuated both in time space (t-x) domain and frequency space (f-x) domain using prediction filters. Abma and Claerbout (1995) discussed both time and frequency approaches to predict linear events and found that f-x prediction is equivalent to t-x prediction when using a long time length. Linear prediction filtering in seismic data is based on the autoregressive (AR) model. According to the AR model, when data is contaminated by random noise, the signal is considered to be predicted by the AR filter and the noise is the residual (Bekara and van Baan, 2009). The f-x prediction technique was first introduced by Canales (1984), and has been further developed by many others.

The f-x prediction method (RANNA) used in this study is based on forward – backward linear prediction (FBLP) theory by Tufts and Kumaresan (1982). Their method solves FBLP in a least-squares sense and used singular value decomposition (SVD) to reduce noise effects.

The f-x prediction technique predicts linear events in the frequency-space domain. We consider a linear event in time space domain with a slope \( p \) and a constant amplitude \( A \). After Fourier transformation it can be represented by

\[
S(f, x) = A(f)e^{j2\pi fxp}
\]

(4.9)

where, \( x \) is the lateral position, \( A(f) \) is the wavelet spectrum, and \( f \) is the temporal frequency.

In Eq. (4.9) we assume \( x = n \Delta x \), where \( n = 1,2,3, \ldots \ldots \ldots \ldots, N \); \( N \) is the number of traces.

For a simple linear event, the function \( S(f, x) \) is periodic in \( x \) and this periodicity can be seen in Fig. 4.12.
The relationship between the nth and the (n-1)th trace can now be predicted from the relationship:

\[ S_n(f) = a_1(f) S_{n-1}(f) \]  \hspace{1cm} (4.11)

where \( a_1 = \exp(j2\pi f \Delta x_p) \) (Gouchang Liu et al., 2012).

F-x prediction is applied in small windows, just to encounter linear events. The data within each window is Fourier transformed and a prediction filter is calculated as described in Eq. (4.11). Each filter is first applied forward and then backward to maintain a symmetrical application. Inverse Fourier Transformation is applied within each window and all the windows are merged to form the output.
4.6 Different data sorting and gathering

Seismic data are normally sorted in the following domains;

- Common Shot gather (CS)
- Common Receiver gather (CR)
- Common Mid-Point gather (CMP)
- Common Offset gather (CO)

**Common Shot gather**

A common shot gather is an initial data sorting and data in this domain gives a continuous subsurface coverage. Each shot provides a slice of the subsurface geology but in a distorted manner, since each successive trace comes from a different receiver and offset (cf. Fig. 4.13a).

**Common Receiver gather**

A common receiver gather represents all traces coming from the same receiver group (cf. Fig. 4.13b). It is not as important in marine acquisition as it is in land where it is commonly used for static corrections.

**Common Mid-Point gathers**

A common midpoint gather represents all traces associated with the same reflection points in the subsurface (in case of horizontal reflectors). This is probably the most important sorting used in seismic data processing. This type of sorting is needed to carry out velocity analysis and NMO correction (cf. Fig. 4.13c).

**Common Offset gather**

A common offset gather represent all traces with the same source receiver distance (offset). This sorting provides a continuous picture of the subsurface geology (cf. Fig. 4.13d).
Figure 4.13: (a) Common shot gather (b) Common receiver gather (c) Common mid-point gather (d) Common offset gather. (Excess Geophysics, www.xsgeo.com).
5 Synthetic Studies

Two blended synthetic data sets are used here:

- Simple data set (A)
- Complicated (Pluto) data set (B)

5.1 Simple synthetic data

This dataset is synthetically blended using NORSAR ray tracing program. The reference was unblended data acquired with the following geometry:

<table>
<thead>
<tr>
<th>Geometry information for data set A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source interval = 25 m</td>
</tr>
<tr>
<td>Number of channels = 481</td>
</tr>
<tr>
<td>Minimum offset = 100 m</td>
</tr>
<tr>
<td>Number of shots = 801</td>
</tr>
<tr>
<td>Maximum offset = 6000 m</td>
</tr>
<tr>
<td>Receiver interval = 12.5 m</td>
</tr>
</tbody>
</table>

This unblended data in the shot domain and the corresponding stacked section is shown in Fig. 5.1.
This unblended data set is then synthetically blended using random delays between 250ms and 750ms, simulating a 2 vessel operation (set up A in section 2.4). The first vessel carried out a standard marine acquisition operation with a 2-D streamer behind (reference data). In addition, a shooting vessel (no streamers) is sailing behind the first vessel and shooting randomly from behind i.e. blended acquisition. There is the same number of shots, i.e. 801 from both vessels. All data are modeled with the NORSAR ray tracing program.
Figure 5.2: (a) Rays associated with a shot point from the conventional vessel. (b) Similar rays associated with the simultaneous shot from vessel behind.

Fig. 5.2a and b show the rays from a single shot associated with respectively the conventional survey and the vessel behind. These two shots are added together to give the blended shot point (see Fig. 5.3).
The unblended source gather shown in Fig. 5.1a now changes to the gather shown in Fig. 5.4a after blended shooting. Correspondingly the stacked section of the blended data is shown in Fig. 5.4b. On comparison with Fig. 5.1b, more noise has been introduced in the section.

5.1.1 Synthetic data set sorted in different domains

The synthetic data set is sorted in different domains to further investigate how the interference from the shooting vessel changes accordingly.
First we consider how synthetic blended data appear in the shot domain.

Figure 5.3: Blended shot obtained by adding the two single shots in Fig. 5.2 (a) and (b).
Figure 5.4: (a) Blended synthetic data in the shot domain. (b) Stacked section of the synthetic blended data.

Shots from the shooting vessel are fired with some random delay as described earlier and this delay can easily be observed in the shot domain (see Fig. 5.5a, b and c).

Figure 5.5: (a), (b) and (c) show examples of the time jitter of the contribution from the shooting vessel behind the streamers.

In the common depth domain (CDP) and in the common receiver domain (CR) interferences from the shooting vessel appear as random noises as shown in Fig. 5.6.
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Figure 5.6: Blended synthetic data in (a) the common depth domain (b) the common receiver domain.

Thus, these two domains transform the deblending problem into that of denoising, since the interferences from the shooting vessel appear as random noise. Seismic processing tools that can remove random noise efficiently can therefore be used to deblend the data.

The blended data in the common offset domain is shown in Fig. 5.7.

Figure 5.7: Synthetic blended data in the common offset domain.
In the common offset domain events associated with front vessel appear as coherent events, while the data associated with the shooting vessel appear as random ‘spikes’. The opposite case will appear if all the random delays of the shooting vessel are corrected for.
5.1.2 Results of FK filtering

Using this method, data is separated or deblended on the basis of their wavenumbers. In blended seismic data, contributions in the source gathers from the conventional (front) and shooting vessels have different dips which will appear at different wavenumbers in FK domain. Thus a FK filter designed based on wavenumbers can be used to separate the blended seismic data. Fig. 5.8 shows a schematics of the procedure.

Figure 5.8: Iterative scheme of FK filtering method

In order to apply FK filtering, seismic data is transformed from time (t)-space (x) domain to frequency (f)-wave number (k) domain as shown in Fig. 5.9.
The slight aliasing that appear in the FK domain could have been removed by reducing the trace interval. The reject filter in FK domain is designed in such a way that all events associated with the conventional vessel are muted away, on the basis of their wave numbers as shown in Fig. 5.9 b and c.

After FK filtering data are transformed back to space-time domain for each shot gather. Fig. 5.10 shows an example of a source gather after FK-filtering.
Although the results from FK filtering show that data are not completely separated, the technique has worked fairly well.

Finally, by subtracting each FK-filtered shot (cf. Fig. 5.10) from the original input gives mostly shots related to the conventional front vessel, as shown in Fig. 5.11c.

**Figure 5.11**: (a) Input blended data in shot domain (b) Results after applying FK filtering. (c) Deblended output in shot domain.

To further evaluate the deblending, a stacked section was formed (cf. Fig. 5.12).

**Figure 5.12**: Steps on how to generate a stacked section in seismic processing.
First, the FK filtered results were sorted in the CDP domain, NMO corrections were applied together with muting to avoid NMO stretch (cf. Fig. 5.13). Finally a stacked section of deblended seismic data was generated as shown in Fig. 5.14.

Figure 5.13: (a) Data sorted in CDP domain. (b) After NMO correction and red line shows the mute design. (c) NMO stretch is muted away.

Figure 5.14: (a) Synthetic deblended stacked section after applying FK filtering. (b) Difference plot between the synthetic blended stack and the synthetic deblended stack processed using FK filtering.
Comments

The difference plot (Fig. 5.1b) shows that FK filtering has partly helped to separate the data but has also removed primary energy (especially in the shallower part of the stack section). Thus FK filtering is not an ideal choice to deblend the data, as follows from the FK analysis of the blended input (Fig. 5.9a) where flat (horizontal) events from both conventional and shooting vessel fall near K=0. Consequently, during the filter design amplitudes of the near offset traces are attenuated. To minimize this effect, a very mild FK filter should be designed.

Another way of estimating the efficiency of FK filtering to deblend the blended data is to compare the RMS energy plots of respectively the blended stack, the deblended stack using FK filtering and the original unblended stack.

Figure 5.15: Comparison of different energy content of input (blended synthetic stack), output (deblended synthetic stack processed using FK filtering) and original unblended stack.

Fig. 5.15 shows the RMS energy distribution for the stacked sections for each CDP location. The energy level of the deblended stack processed using FK filtering is rather similar to that of the original unblended stacked section. However, the energy level is overall lower indicating that some primary energy has also been removed.
**FK filter with TFDN**

In the next test the FK filtered results were used in combination with TFDN to further improve the deblending and remove some artifacts.

TFDN is applied in the CDP domain so it works directly on the result shown in Fig. 5.13c. In the CDP domain the interferences from the shooting vessel appear as random noise and TFDN is an efficient technique to remove the random noise.

After applying TFDN, a new stacked section is generated as shown in Fig. 5.16b.

![Figure 5.16: (a) Synthetic deblended stacked section processed using FK Filtering and TFDN. (b) Difference plot between the synthetic blended stack and the synthetic deblended stack processed by FK filtering and TFDN.](image)

**Comments**

It can be seen from Fig. 5.16 on comparison with Fig. 5.14 that more cross-talk noise has been removed. However, the TFDN technique cannot restore the loss of primary energy due to FK filtering.
5.1.3 Tau-p filtering results

This method separates or deblends the data on the basis of dips, in the tau-p domain. In blended seismic data, contributions in source gathers from front and behind (conventional and shooting vessel) have different dips and these different dips can be more easily separated in the tau-p domain.

The tau-p filtering method is applied schematically as shown in Fig. 5.17.

![Figure 5.17: Iterative scheme of the tau-p filtering method.](image)

An interpolation (input traces were doubled from 481 to 962) was carried out to make dips more elaborate in the tau-p domain and to minimize the aliasing in the data.
Fig. 5.18 illustrates how a source gather looks in the tau-p domain. The horizontal axis represents the ‘p’ values corresponding to actual dips in the time domain and the vertical axis represents the tau values (time intercepts). The dotted black line represents the ‘p=0’ value i.e. events with zero-dips fall here.

A reject filter is designed in the tau-p domain in such a way that only negative dips are preserved, corresponding to contributions related to the shooting vessel. Thus ideally it should filter only the positive dips, the final result (Fig. 5.18b) shows that also some of the negative dips have been filtered. By transforming back the filtered results from the tau-p domain to the time-space domain, contributions related to the shooting vessel dominate in Fig. 5.19b. This result is then subtracted from the input data that eventually leads to the deblended data in the shot domain (cf. Fig. 5.19c).
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Figure 5.19: (a) Input blended data in shot domain (interpolated traces). (b) Results after applying reject filter in tau-p domain. (c) Deblended result processed using tau-p filtering.

Fig. 5.20a shows the deblended stacked section processed using tau-p transformation and Fig. 5.20b shows the difference plot between the deblended stacked section and the blended stacked section.

Figure 5.20: (a) Synthetic deblended stack section processed by using filtering in tau-p domain. (b) Difference plot between the synthetic blended stack and synthetic deblended stack processed by using tau-p filtering.
Comments

The difference plot shows that this method has been harsh in the shallower part of the stacked section especially up to 2 seconds (very similar to FK Filtering). But the lower part of the stacked section shows that data have been efficiently separated.

Fig. 5.21 shows comparisons of the RMS energy levels of respectively the synthetic blended stack, the unblended stack and the deblended stack shown in Fig. 5.20a.

The energies show that the deblended stack shows very similar quality as the unblended stack but with a lower energy level in general.

![Energy content comparison](image)

*Figure 5.21: Comparison of different energy content of input (blended synthetic stack), output (deblended synthetic stack processed using tau-p filtering) and original unblended stack.*

As in the case of FK filtering, this is due to the removal of primary energy. Direct comparison between Fig. 5.15a & 5.20a show that tau-p perform slightly better than the FK filtering.
5.1.4 Time Frequency Denoising (TFDN)

Next, we tried to separate the blended seismic data by using TFDN. As discussed earlier, the interferences from the shooting vessel appear as random noise in the CDP domain (as shown in Fig. 5.6). Therefore it is preferable to use TFDN in the CDP domain.

![Figure 5.22: Iterative scheme of TFDN.](image)

In this study we run several iterations of TFDN as indicated in Fig. 5.22. In TFDN a user defined window slides over the traces in the frequency and space domain, and all parameters are adjusted by the user according to the noise contribution in the seismic data. Here we ran four iterations of TFDN in the CDP domain, followed by NMO correction and stacking.

Fig. 5.23a shows the deblended synthetic stack processed using TFDN and Fig. 5.23b shows the difference plot between the unblended synthetic stack processed by using TFDN and the blended synthetic stack.
Figure 5.23: (a) Synthetic deblended stack processed using TFDN. (b) Difference plot between the synthetic blended stack and the synthetic deblended stack processed using TFDN.

Comments

The difference plot shows that TFDN has not been harsh to the primaries and what has been separated from the input data is noise only. However some noise is left between 2 and 3 seconds as shown in Fig. 5.23a.

The same can be observed from the RMS energy levels shown in Fig. 5.24 where the original unblended stack and the deblended stack almost overlap each other.
Figure 5.24: Comparison of different energy content of input (blended synthetic stack), output (deblended synthetic stack processed using TFDN) and original unblended stack.

Since TFDN has virtually not removed any primary energy, it performs significantly better than both the FK-filtering and the tau-p approaches.

Table 1 summarizes the performance of each denoising approach together with corresponding running times

<table>
<thead>
<tr>
<th>Method applied</th>
<th>Results</th>
<th>Running Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FK Filtering</td>
<td>fair</td>
<td>3hrs.</td>
</tr>
<tr>
<td>FK filtering + tau-p filtering</td>
<td>fair</td>
<td>6hrs.</td>
</tr>
<tr>
<td>Tau-p filtering</td>
<td>fair</td>
<td>5hrs.</td>
</tr>
<tr>
<td>TFDN</td>
<td>very good</td>
<td>7hrs.</td>
</tr>
</tbody>
</table>
5.2 Pluto Data (Complicated)

The Pluto data set is also a synthetically blended data set corresponding to set up A. The data are more complicated as compared to the previous synthetic data as can be seen from the blended stack in Fig. 5.25 b. It is clear from Fig. 5.25 a that the time delay between the shots from the two vessels (front and behind the streamer) is very small, which makes deblending a real challenge.

Figure 5.25: (a) Synthetic blended data in shot domain. (b) Synthetic blended stack.

Fig. 5.26 shows the original unblended data set both in the shot domain and as a stack.
The unblended synthetic data has the following acquisition geometry:

<table>
<thead>
<tr>
<th>Geometry design for Pluto dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source interval = 50 m</td>
</tr>
<tr>
<td>Number of channels = 126</td>
</tr>
<tr>
<td>Minimum offset = 100 m</td>
</tr>
<tr>
<td>Number of shots = 1261</td>
</tr>
<tr>
<td>Maximum offset = 9475</td>
</tr>
<tr>
<td>Receiver interval = 50 m</td>
</tr>
</tbody>
</table>

The methods used to deblend the Pluto data set are the same that I used previously to deblend the simple synthetic data.
5.2.1 Pluto synthetic data set sorted in different domains

The synthetic data set was first sorted in different domains to make it more clear how the interferences from the shooting vessel appear in the different sortings. The shot domain data have already been shown in Fig. 5.25a and 5.26b (blended and unblended synthetic data respectively). In the common depth domain (CDP) and in the common receiver domain (CR) interferences from the shooting vessel appear as random noise, therefore different filters are designed in these two domains to separate or deblend the blended data.

Fig. 5.27a and b show the data in common depth and common receiver domain respectively. In both domains interferences from the shooting vessel does appear as random noise but this random noise is not as clearly distinguishable from the coherent events as they were for the simple synthetic data.

Fig. 5.27: Blended synthetic data in (a) CDP domain and (b) in the common receiver domain.

Fig. 5.28 shows the blended synthetic data in the common offset domain. In this domain events related to the shooting vessel appear as random spikes. This domain represents the subsurface geology structure well, and it is obvious from the Fig. 5.28 that this synthetic data represents a complicated subsurface.

Interferences from the shooting vessel appear as random spikes.
Figure 5.28: Blended synthetic data in the common offset domain.
### 5.2.2 Results of FK filtering

FK filtering is applied here in the same way as discussed earlier in section 5.1.2. Data are first transformed into frequency-wave number (FK) domain and then a reject filter is designed in such a way that all contributions related to the shots from the shooting vessel are kept (see Fig. 5.29a, b and c).

![Shot from the shooting vessel](image1)

![Shot from the conventional vessel](image2)

**Figure 5.29:** (a) FK transformation of Pluto synthetic blended data. (b) Dotted rectangle shows design of reject filter in FK domain. (c) Filtered section in FK domain.

Next, the FK filtered results are transformed back to the time-space domain. Ideally, only contributions from the shooting (behind the streamer) vessel should be left.

Fig. 5.30b shows the separated events after FK filtering. By subtracting those from the input shown in Fig. 5.30a deblended data in the shot domain can be obtained as shown in Fig. 5.30c.
Figure 5.30: (a) Input Pluto blended data in shot domain (b) Results after applying FK filtering. (c) Deblended output in shot domain.

From Fig. 5.30 it follows that FK filtering has removed the blending noise fairly well and it seems that this method has not been too harsh to the data.

Fig. 5.31a shows the stack of the deblended data (processed using FK filtering) whereas Fig. 5.31b shows the difference plot between the Pluto blended stack shown in Fig. 5.25b and the deblended stack.
Comments

The stacked section (shown in Fig. 5.31a) when compared to Fig. 5.26b (Unblended) shows that the FK filtering approach to deblending is not a good choice. It has been really harsh to the amplitudes and dips of the reflectors. One possible reason is that traces related to flat events from both conventional and shooting vessel appear near K=0 in the FK-spectrum. Consequently a very mild filter has been designed in the FK domain to keep the data from the conventional vessel unaffected. This fact leads to the poor deblending results.

Another interesting observation is that the data appear apparently to be deblended or separated more successfully when considered in the shot domain as shown in Fig. 5.30c, but the corresponding stack does not give the same optimal deblending results.

Fig. 5.32 shows a comparison of the RMS energy levels for respectively the unblended and deblended stack.
Figure 5.32: Comparison of RMS energy level of the unblended synthetic stack and the deblended synthetic stack processed using FK filtering.

Ideally, the energy level of the deblended stack (black curve) should be similar to that of the unblended original stack. But the differences in energy level show that FK filtering has given poor deblending results by removing too much primary energy.
5.2.3 Results of SVDMUL

We propose to apply SVDMUL in an iterative way to deblend the blended seismic data. The main idea is that the contributions from the shooting vessel also can be made coherent by applying proper time shifting. This will make the contribution from the conventional vessel incoherent. (Maraschini et. al. 2012)

The iterative scheme used for SVDMUL is summarized in Fig. 5.33.

![Figure 5.33: Iterative scheme of SVDMUL](image)

First data are sorted into common offset (trace) domain and the SVDMUL module is applied. In the following we will use the following notation to ease the discussion:

Data set A: shots related to the front conventional seismic vessel.
Data set B: shots related to the shooting vessel.
Figure 5.34: (a) Pluto synthetic data in common offset (trace) domain. (b) Eigen images (first four and the last one)

The Uniseis SVDMUL tool decomposes the data into a set of orthogonal components, and these components are dependent on the degree of variance in the dataset. The first 3 or 4 components (eigen images) contain the coherent events in the data and the remaining ones random contributions (see Fig. 5.34b). The SVDMUL module is run twice per iteration as follows:

- **SVDMUL1:**
  Data are input as they are which implies that data set A appear coherent (steps 3 and 4 in Fig. 5.33). SVDMUL is applied and the first four components containing coherent events are removed so only the noisy part is preserved.

- **SVDMUL 2:**
  Then we apply time shifts to make data set B coherent and A appears as random noise, (steps 5-7 in Fig. 5.33).
  Fig. 5.35 shows an example of data set B in the common offset domain.
Figure 5.35: Pluto synthetic data in common offset domain after time shifts have been applied to make the shots from the shooting vessel coherent events.

The SVDMUL module is again applied, and only the first two components containing the coherent events are kept (dataset B).

In both steps (SVDMUL 1&2) we are keeping mainly the contributions related to the shooting vessel. The next step is to subtract this part (from SVDMUL 1&2) from the input dataset (Step 8 in Fig. 5.33). The result obtained after the first iteration is shown in Fig. 5.36a. This process is repeated 10 times and Fig. 5.36b shows the results obtained after 10 iterations (common offset domain).
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Figure 5.36: (a) Result after 1 iteration (b) result after 10 iterations (common offset domain).

Fig. 5.37 shows how the RMS energy difference between the output at a given iteration and that of the previous one vary with iteration number. In case of an iteration number above 10, this curve did not essentially change.

Figure 5.37: RMS energy difference for each iteration
Finally Fig. 5.38a shows the stack obtained after iterative SVDMUL and Fig. 5.38b shows the difference plot between the Pluto blended stack shown in Fig. 5.25b and the deblended stack section processed by using SVDMUL.

![Figure 5.38: (a) Pluto synthetic deblended stack processed using SVDMUL. (b) Difference plot between the Pluto synthetic blended stack and the synthetic deblended stack processed by SVDMUL.](image)

**Comments**

The difference plot in Fig. 5.38b shows that this approach has worked quite well since the plot contains only random noise, thus not being harsh to the amplitudes.

Fig. 5.39 shows a comparison of the RMS energy levels for respectively the Pluto synthetic unblended stack and the deblended stack processed using SVDMUL. The deblended stack has a similar energy level as the unblended stack in general.
Figure 5.39: Comparison of RMS energy level for the unblended synthetic stack and the deblended synthetic stack processed using SVDMUL.
5.2.4 Tau-p filtering results

The blended synthetic seismic data were now transformed to tau-p domain and a mute (reject filter) was designed which tends to keep only contributions related to the conventional seismic vessel (cf. Fig. 5.40). The process is similar to the one described in section 5.17 for the simple synthetic data set.

Figure 5.40: (a) Tau-p transformation of Pluto synthetic blended seismic data. (b) After applying mute in tau-p domain. (c) The corresponding source gathers after filtering.

Fig. 5.40c shows the events related to the shooting vessel that are separated by using tau-p filtering. It can be observed that this method failed to attenuate the events related to the conventional vessel has also been harsh to the amplitudes of the shooting vessel events. The next step is to subtract this result from the input shot gather (cf. Fig 5.41), and make a stacked section following the steps in Fig. 5.12. The corresponding stack obtained after filtering in the tau-p domain is shown in Fig. 5.42 a and the corresponding residual stack is given in Fig. 5.42 b.
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Figure 5.41: (a) Input Pluto blended data in shot domain (b) Results after filtering in tau-p domain. (c) Deblended output in shot domain.

Figure 5.42: (a) Pluto synthetic deblended stack processed using tau-p filtering. (b) Difference plot between the Pluto synthetic blended stack and the synthetic deblended stack processed using tau-p filtering.

Comments

It follows from Fig. 5.42b that the tau-p approach has failed and too much primary energy has been removed. This result is worse than in case of the simple synthetic data example where only gently dipping reflectors were considered.
Fig. 5.43 supports the same conclusion showing that the deblended stack processed using tau-p filtering has a very different energy level as compared to the unblended stack.

Figure 5.43: Comparison of RMS energy levels of the unblended original Pluto synthetic stack and the deblended synthetic stack processed using tau-p filtering.
5.2.5 TFDN Results

TFDN is used to deblend the Pluto synthetic data in the same way as for the simple synthetic data in section 5.1.4. It is applied in the CDP domain and iteratively, i.e. both before applying NMO correction and also after. The parameter selection of the TFDN windows had to be tested to comply with the noise contribution in the Pluto synthetic data.

Figure 5.44: (a) Pluto synthetic deblended stack processed using TFDN. (b) Difference plot between the Pluto synthetic blended stack and the synthetic deblended stack processed using TFDN.

Comments

The deblended synthetic stack obtained by using TFDN is shown in Fig. 5.44a, where some of the random noise has been removed. However the difference plot shown in Fig. 5.44b shows that TFDN has also been harsh to the amplitudes of the events related to the conventional vessel.
The same observation follows from the RMS energy levels plotted in Fig 5.45, showing that the deblended stack in general has a lower energy level than the corresponding unblended one.

Another important reason for the somewhat poor results of TFDN (also shown earlier in case of the simple synthetic data set) is that the interference from the shooting vessel in the CDP domain appear with high amplitudes and are no more separable from the conventional vessel contributions in the deeper part as shown in Fig. 5.27a.

Also the fx-prediction technique (module RANNA) was tested on this data set, but gave poor results (see the Appendix A.2). It was observed that f-x filtering could not preserve the amplitudes of the primary data. Due to its poor performance this method is not tested for the real dataset.
Table 2 summarizes the performance of each denoising approach together with run time in case of Pluto of synthetic data.

Table 2: Summary of performances

<table>
<thead>
<tr>
<th>Method applied</th>
<th>Results</th>
<th>Running time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FK filtering</td>
<td>Poor</td>
<td>5hrs.</td>
</tr>
<tr>
<td>Tau-p filtering</td>
<td>Poor</td>
<td>9hrs.</td>
</tr>
<tr>
<td>TFDN</td>
<td>Fair/good</td>
<td>11hrs.</td>
</tr>
<tr>
<td>SVDMUL</td>
<td>Very good</td>
<td>30hrs.</td>
</tr>
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</table>
6 Field data example

The data was acquired in a shallow water environment in the Eastern Mediterranean Sea (using set up A). Random time delays between [0ms, 500ms] were used. Also an unblended dataset was acquired and could be used as a reference. Although originally 3D data, I used only one line here so I considered it as a 2D dataset.

The geometry used to acquire the unblended data was as follows:

<table>
<thead>
<tr>
<th>Geometry design of Real dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source interval = 50 m</td>
</tr>
<tr>
<td>Number of channels = 636</td>
</tr>
<tr>
<td>Minimum offset = 100 m</td>
</tr>
<tr>
<td>Number of shots = 254</td>
</tr>
<tr>
<td>Maximum offset = 7950 m</td>
</tr>
<tr>
<td>Receiver interval = 12.5 m</td>
</tr>
</tbody>
</table>

Fig. 6.1a shows the original unblended data in the shot domain and Fig. 6.1b shows the corresponding stack of this unblended data.

Figure 6.1: (a) Unblended data in shot domain. (b) Stack of unblended seismic data.
The unblended and blended surveys followed the same sail line, and also sharing the same acquisition parameters. The only difference was the number of shots in case of blended data being 254.

Fig. 6.2a shows the blended seismic data in the shot domain and Fig. 6.2b shows the corresponding stack of the blended data.

![Figure 6.2: (a) Real blended data in shot domain. (b) Stack of blended seismic data.](image)

Direct comparison between the unblended and blended stacks (Fig. 6.1b and 6.2b) shows that the blended stack section have more details. But signal to noise ratio is lower, which can be more easily seen in the zoomed parts of these stacks shown in Fig. 6.3. By comparing the events inside the yellow and green circles in Fig. 6.3, it can be observed that in the blended stack reflectors appear with more continuation giving some extra detail about the subsurface geology.

But one can also easily see the higher noise contribution in the blended stack as compared to the unblended one. Blending interferences from the shooting vessel manifest themselves with higher amplitudes than those of the signal that we want to preserve (signals of the conventional front vessel). This problem makes the deblending a challenging job in processing.
The stacked sections show that the subsurface structure is fairly simple and consist of relatively flat reflectors as compared to the Pluto synthetic data set (discussed in sub chapter 5.2).

![Unblended stack](image1)

![Blended stack](image2)

![Zoom of data within red rectangle shown in (a)](image3)

![Zoom of data within black rectangle shown in (b)](image4)

Figure 6.3: (a) Unblended stack. (b) Blended stack. (c) Zoom of data within red rectangle shown in (a). (d) Zoom of data within black rectangle shown in (b).

6.1 Blended data set sorted in different domains

The real blended data were sorted in different domains to further investigate the behavior of interferences from the shooting vessel when using various data sorting.
Fig. 6.4a shows the blended seismic data in the CDP domain and Fig. 6.4b shows the blended seismic data in the Common receiver domain. In both of these domains interferences from the shooting vessel appear as random ‘spikes’. But the character of these random ‘spikes’ make them difficult to separate from the contributions related to the conventional vessel in the deeper part. This is the reason why TFDN method has not been applied to this data set.

![Image](image_url)

**Figure 6.4:** (a) Blended data in the CDP domain. (b) Blended data in the common offset domain.

Fig. 6.5 shows the blended data sorted in the common offset domain. This domain gives a ‘picture’ of the subsurface geology, and it seems that in this domain mostly random noise dominate below 5 seconds.
Figure 6.5: Blended data in the common offset domain
6.2 Results of FK Filtering

In this thesis work FK filtering was used in two ways:

Approach 1:
Transformation of the blended seismic data from the space-time domain (shot gathers) to the FK domain and design of a reject filter to separate or deblend the data.

Approach 2:
Sorting the blended seismic data from shot domain to CDP domain followed by a NMO correction. Then transformation to FK domain and design of a filter to separate or deblend the data.

In this section we will only discuss results obtained employing Approach 1. Approach 2 gave poorer results and is summarized in Appendix A.1

6.2.1 FK filtering results (Approach 1)

FK filtering using Approach 1 is shown in Fig. 6.6. The filter is designed complementary to the one discussed earlier in Fig. 5.8. Thus it tends to keep only the events associated with the conventional vessel (opposite to the filter design in sections 5.1.2 and 5.2.2)
Investigating Different Approaches of Deblending Seismic Data

Figure 6.6: (a) FK transformation of real blended data. (b) Dotted rectangle shows design of filter in FK domain. (c) Filtered source gather in FK domain.

The output from the filter design in the FK domain are source gathers with contributions from the shooting vessel being enhanced. (see Fig. 6.7).

Figure 6.7: Results of FK filtering.

A simple front end mute is then used to further remove the interferences coming from the shooting vessel (see red dotted lines in Fig. 6.7).

It can be clearly seen that the FK filtering results are not too promising. This conclusion is also supported by considering the corresponding stacked section and the residual stack (see Fig 6.8).
Investigating Different Approaches of Deblending Seismic Data

Figure 6.8: (a) Deblended stack using FK filtering. (b) Difference plot between the blended stack and deblended stack processed using FK filtering.

Comments

FK filtering has been really harsh to the amplitudes and at shallower part of the stack it has clearly ‘washed’ out all events.

One reason for this poor result is that the time delays between the shots (front and back vessel) are very short making them less separable in the FK domain.

Fig. 6.9 shows the RMS energy levels of the original unblended stack and the deblended stack processed using FK filtering. It can be easily seen that too much energy have been removed.
Figure 6.9: Comparison of RMS energy level of the unblended original stack and the deblended stack processed using Uniseis FK filtering
6.3 Tau-p filtering results

The blended data is now deblended using tau-p filtering. A mute function is designed in this domain that tends to keep the contributions related to the shooting vessel. These events are further subtracted from the input blended data in order to give data with contributions from the conventional vessel being enhanced (deblended shots). The method is the same as described in sections 5.1.3 and 5.2.5.

Fig. 6.10a and b show respectively the tau-p transformation of the input blended data and the design of the mute function. Fig. 6.10c shows the filtered source gather after this mute function has been applied.

As the result in Fig. 6.10c still contains interferences from the conventional vessel but events related to the shooting vessel are more enhanced. The next step is to subtract this result from the input shot gather (cf. Fig 6.11), and generate the stacked section following the steps in Fig. 5.12. The corresponding stack obtained after filtering in the tau-p domain is shown in Fig. 6.12a and the corresponding residual stack is given in Fig. 6.12b.
Figure 6.11: (a) Tau-p transformation of real blended seismic data. (b) After applying mute in tau-p domain. (c) The corresponding source gather after filtering.

Figure 6.12: (a) Deblended stack processed using tau-p filtering. (b) Difference plot between the blended stack and the deblended stack processed using tau-p filtering.

Comments

From Fig. 6.12 it follows that the tau-p filtering approach has worked quite well, and the difference stack shows that, except for very shallow parts, only random noise has been virtually removed.
This conclusion is also supported by the RMS energy levels shown in Fig. 6.13. The reason for this good result is that mainly gentle reflectors exist with no conflicting dip. The contributions related to both vessels (front and back) appear separately in the tau-p domain and makes it possible to decompose the blended data in this domain.

Figure 6.13: Comparison of RMS energy level of the unblended original stack and the deblended stack processed using tau-p filtering.
6.4 SVDMUL results

SVDMUL is used in an iterative way to deblend the blended seismic data. The approach used follows the same steps as described in section 5.4.

The data is sorted in the common offset domain, and SVDMUL is applied in a way so that it only tends to keep the noisy part (by excluding the first 3 Eigen images). Then the time delays between the two shots (front and back) are applied to transform the shot responses related to the shooting vessel to be coherent. SVDMUL is applied again and the coherent part is kept (represented by the first 2 Eigen images). In both cases we are keeping events that are related to the shooting vessel and which can finally be subtracted from the input to give separated or unblended data.

Here SVDMUL was applied in 10 iterations, in each iteration the intention is only to separate random energy from coherent events to make data unblended. We can use more than 10 iterations but it makes the process more time consuming without gaining significant improvements for this data set.

Fig. 6.14 shows ten Eigen images created for this data set, the first three or four (starting from left) contain most of the coherent energy.

Figure 6.14: Eigen images for real data set, the first four images contain coherent events while the remaining consists of mostly random noise.
Fig. 6.15 shows comparison of SVDMUL results in the common offset domain. Fig. 6.15c and d show how effectively SVDMUL has removed the random noise in this domain.

![Figure 6.15: Blended data (a) in common offset domain (b) results after applying 10 iterations (c) zoomed part of (a), (d) zoomed part of b.](image)

Fig. 6.16 shows the RMS energy difference for each iteration. After ten of more iteration no further improvement was obtained in this residual energy.
Finally Fig. 6.17a shows the deblended stack processed using 10 iterations of SVDMUL. Fig. 6.17b shows the difference plot between the blended stack and the deblended stack.

Comments

The difference plot in Fig. 6.17b shows that this process has removed most of the random noise but it has also been a bit harsh to the amplitudes in the encircled areas. The reason is that the
time delays between the two shots (front and back) are not so accurate so by applying the time shifts some artifacts may be introduced.

Figure 6.18: Comparison of RMS energy level of the unblended original stack and the deblended stack processed using SVDMUL.

The RMS energy curves shown in Fig. 6.18 also support this conclusion: the deblending has worked quite well for larger parts of the data but in some areas too much energy has been removed.

Table 3 summarizes the performance of each denoising approach together with run times in case of the real data set.
Table 3: Summary of performance

<table>
<thead>
<tr>
<th>Method applied</th>
<th>Results</th>
<th>Running time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FK filtering</td>
<td>Poor</td>
<td>2 hrs.</td>
</tr>
<tr>
<td>Tau-p filtering</td>
<td>Very good</td>
<td>7 hrs.</td>
</tr>
<tr>
<td>TFDN</td>
<td>Failed</td>
<td></td>
</tr>
<tr>
<td>SVDMUL</td>
<td>Very good</td>
<td>24 hrs.</td>
</tr>
</tbody>
</table>
7 Migration

7.1 Migration

Migration is the process that intends to move seismic stacked data into their correct position both in time and space. In post stack migration, as considered here, the main assumption is that a stacked section is close to that of zero offset. In a stack all seismic responses are plotted vertically. Thus for all subsurface models different from a horizontally layered one, this will lead to distortions (see Fig. 7.1)

Figure 7.1: The true position of the reflector in depth differs from its position on the time section. (Blue Nile).

Post stack migration then tries to compensate for such distortions based on wave theory. The main effects of migration are:

- Diffractions are collapsed to points.
- Dipping reflectors move up dip and become steeper.
- Bow ties associated with synforms are unwrapped.

Fig. 7.2 gives an example of post-stack migration
Figure 7.2: (a) Geological model (b) seismic section (c) seismic section after migration. (Blue Nile).

The migration process removes the effect of wave propagation through the subsurface and focuses the seismic events back to their correct subsurface positions. (Blue Nile). Migration can
be applied both pre-stack and post-stack. Pre-stack migration is more time consuming as compared to post-stack migration. In this study we will therefore only use post-stack (Kirchhoff) migration.

![Real blended stack](image1)

**Figure 7.3: Real blended stack (a) before migration, (b) after migration.**

Fig. 7.3 shows the blended stack before and after migration. Migration has filtered the random noise and enhanced the reflections. Fig. 7.3b shows that after migration reflectors become more strong and clear in the deeper part of the section.

Next, migration was applied to a deblended stack in order to compare it with the result shown in Fig. 7.3b. In this comparison the tau-p filtered result is used as a reference deblended stack. Fig. 7.4 shows the results after migration of the deblended stack. It can be clearly seen from the Fig. 7.4 b that the result is very similar to the blended migrated section (*cf.* Fig. 7.3b).
Figure 7.4: Real deblended stack (a) before migration (b) after migration.

Comments

Fig. 7.5 shows the difference plot between the blended stack and the deblended stack after migration.

Figure 7.5: Difference plot between blended and deblended stacks after post stack migration.

Fig. 7.5 demonstrates that there are very little visible differences between the blended and deblended stack after migration, except in the very shallow part of the difference plot. Thus the deblended and blended sections provide essentially the same final images after migration.
Chapter 8
Discussion and Conclusions

The main purpose of this thesis has been to investigate possible approaches to deblend seismic data. Based on early work in the literature, the key idea have been to either transform the problem to that of denoising by sorting the blended data in proper domains, or to separate the data based on differences in slope (dip).

Note that the work presented here is limited to one possible configuration to be used in blended data acquisition (or shooting). Normally the case where a shooting vessel follows the tail-buoy of the conventional streamer vessel. This type of acquisition gives two sets of data simultaneously where the CMP swath is illuminated from both sides with an $180^0$ differences in azimuth. For such blended shooting the contributions from two vessels look quite different because of differences in the main dips. However, the case of a wide-azimuth type of blended shooting where the seismic vessels and the shooting vessel are aligned parallel to each other. This configuration gives more complicated data to deblend because of the more similar characteristic of the two mixed shots.

In this thesis three different data sets have been employed to validate the different denoising and separation approaches. Two of the data sets were synthetically generated, one being quite simple and the other one more complex (the ‘Pluto’ data set). The field data set was acquired in a shallow water environment in the Eastern Mediterranean Sea.

In the following we will summarize the main observations made for each of the applied methods. In the case of FK and tau-p filtering the idea was to separate the events based on difference in slope or dip. In the case of TFDN the idea was to sort data into CMP and/or common offset, so that the blending problem appeared like that of denoising. In case of SVDML, the data was also sorted to transform the problem into one of denoising, and the coherent and incoherent parts were decomposed in Eigen-images.
8.1 Separation in Slope/Dip

The first technique employed was FK-filtering. The results obtained were not satisfactorily. Large parts of the coherent energy were removed, which is highly unwanted. The reason why this technique does not work is most likely because the contributions from the two shots being mixed, characterized by small slopes easily mix in the FK domain. It also depends on the apparent dips on the shot gather, for smooth and merged dips they will not be well distributed on FK spectra. Therefore, design of reject filter that effectively decompose the blended data is challenging.

In case of tau-p filtering the results obtained for the real field data set was very good. It separated the blending events efficiently. But it failed to deblend the data where subsurface geology was complicated (e.g. Pluto data set). Tau-p filtering method is being a good choice in deblending if the subsurface is expected to have simple geology. In areas with conflicting dips and complicated geology this method do not have good applicability.

8.2 Denoising approach

The TFDN technique performed quite well on the two synthetic data sets. The idea of transforming the deblending to that of denoising seems to be sound. However, when applied to the real data set, the result was disappointing. The main reason is probably due to the small time delays used for blending, which makes the noise separation less ideal.

Finally, SVDML was applied to both the Pluto and real data set. This technique was applied in an iterative manner where the contributions related to the shooting vessel were made coherent by applying proper time shifts. This method seemed to separate the signal from the noise in a very efficient manner. Combined with the iteration formation, SVDML gave the overall best results with a good margin. However, compare to the other approaches, the computational time is considerably higher.

Up till now we have discussed how to deblend seismic data pre stack. If pre stack is not an issue and only a final migrated image is of interest, deblending seems not so important. This is reported earlier in literature among others Berkhout (2008). In this study we also tried to verify if
this is the case from the real data used here. The blended stack and deblended (in this case based on tau-p filtering which seemed to work well) were post stack time migrated. The final results were very similar except for very shallow part.
Appendix A

A.1 FK filtering results (second approach)

FK filtering is now applied as schematically shown in Fig. A.1.

**Figure A.1:** Schematics of FK filtering (second approach).

Fig. A.2 (a) shows the NMO corrected traces in the CDP domain, Fig. A.2b part shows the design of the filter in the FK domain and Fig. A.2c shows the filtered CMP in FK domain.
The basic idea behind this approach is that the NMO corrections flatten the reflectors (related to the conventional vessel shots) and after FK transformation these events will appear close to K=0. A filter is then designed in such a way that it keeps only this portion around K=0.

After transforming back from FK domain to the space-time CDP domain and muting of the NMO stretches a stack can be formed.

Fig. A.2a shows the deblended stack processed using FK filtering and Fig. A.2b shows the difference plot between the deblended stack (processed using FK filtering) and the blended stack.
Figure A.3: (a) Deblended stack using FK filtering. (b) Difference plot between the blended stack and the deblended stack processed using FK filtering.

Comments

By considering the difference stack in Fig. A.3b one can easily see that the deblending has not been very successful. The same conclusion follows from the RMS energy plot shown in Fig. A.4.

Figure A.4: Comparison of RMS energy level of the unblended original stack and the deblended stack processed using Uniseis FK filtering.
**A.2 F-x prediction (Ranna) results**

The Uniseis module Ranna is now used to deblend the Pluto blended data. This module is based on the F-x prediction method. Ranna is preferably applied to NMO corrected traces in the CDP domain. It is applied in small windows and finally these windows are merged to form the output. Fig. A.5a shows the Pluto deblended stack processed using the Ranna module. We used 5 iterations of Ranna and the residual stack (Fig. A.5b) shows that the method has failed.

![Pluto synthetic deblended stack processed using Ranna](image)

*Figure A.5: (a) Pluto synthetic deblended stack processed using Ranna. (b) Difference plot between the Pluto synthetic blended stack and the synthetic deblended stack processed using Ranna.*

**Comments**

Even though the Uniseis Ranna module has cleaned the random noise (appearing in the Pluto synthetic stack section due to blending), it has been too harsh to the primary energy.

This also follows from the RMS energy levels plotted in Fig. A.6 (i.e. too much energy removed).
Figure A.6: Comparison of RMS energy level of the unblended original Pluto synthetic stack and the deblended synthetic stack processed using Uniseis Ranna module.
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