Shot repetition: an alternative approach to blending in marine seismic

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Summary

Deblending algorithms based on current blended acquisition design often require a dense source sampling to ensure a high-quality result. However, in practice the spatial source sampling is usually too coarse. In this abstract, we discuss an alternative approach to blending in marine seismic, called shot repetition, which can overcome this requirement. Shot repetition refers to activating a broadband source more than once at the same location. We extend the general forward model of source blending to include the case of shot repetition. By exploiting the repetitive shots acquired at the same location, deblending can be implemented in the common-shot domain, and therefore our method has no restrictions on source sampling. We applied the method to numerically blended field data and obtained satisfactory results.

Introduction

Blended acquisition, which is also known as simultaneous-source acquisition, is becoming increasingly popular because it combines a higher data quality with better economics (Long et al., 2013). Deblending, the process where blended shot records are turned into regular shot records, is needed before conventional seismic data processing.

A blended acquisition should be designed such that the acquired data can be successfully deblended. To that end, the blended sources are coded in acquisition and decoded in processing. In land seismic surveys, the vibroseis source codes are near-orthogonal sweeps. In marine seismic surveys, however, only time encoding has been successfully applied to the impulsive sources involved, such as airgun arrays.

In marine seismic acquisition, a simple method for source encoding in time is to apply random time delays to the blended inline sources (see e.g. Vaage, 2002). To deblend such data, the sources are aligned by removing the random time code, i.e., pseudo-deblending. After psedudo-deblending (Berkhout, 2008), the response of the aligned sources is coherent in another domain, e.g. the common-receiver domain, while the blending noise appears incoherent. The blending noise can then be removed by a coherency filter in an iterative scheme (Mahdad et al., 2011). This deblending method is effective when the blended data has a dense source sampling. However, it starts to break down when the source sampling becomes sparse.

Many approaches of marine source encoding have proved that near-orthogonal source codes help achieving goals such as enhancing the signal and removing the interference. Barbier and Viallix (1973) introduced the Sosie method where the source energy released in the water is split into a sequence of discrete pulses that has a spiky autocorrelation function. In the so-called Popcorn shooting (Abma and Ross, 2013), airguns in one source array are activated individually to form near-orthogonal sequences. Popcorn type of source encoding in a blended experiment allows effective deblending (Mueller et al., 2014). The deblending of popcorn type of blended data uses deconvolution of the source signature and solves it by sparse inversion.

We propose an alternative approach to blending, called shot repetition, to overcome being restricted to a dense source sampling. Shot repetition refers to activating a broadband source more than once at the same location. Benefitting from the repetitive information acquired at the same location, the deblending process can be applied per individual shot record. In a blended experiment, the shot-repetition codes can be designed near-orthogonal, similar to Mueller et al. (2014), showing a spiky autocorrelation function and small cross-correlation values.

In the deblending stage, our method also takes advantage of a sparse inversion. This inversion is based on the general forward model of source blending (Berkhout, 2008). The great benefit of this is that we can easily combine shot-repetition codes with other blending codes, such as random time delays applied to the blended inline sources, to increase the deblending power. In addition, shot repetition has favorable properties on reducing noise.

In this abstract, we start by discussing the forward model of shot repetition. This model is used for constructing our iterative deblending method. The blending and deblending processes are illustrated with numerically modeled data, where two sources are blended (i.e. the blending factor is two), and each source is activated eight times at the same location. The deblended results are presented with field data, which is blended numerically in the same convention. Nevertheless, shot repetition is a general concept, which can be applied in the case of larger blending factor and any number of repetitions.

The forward model of shot repetition

The forward model of shot repetition is extended from the general forward model of source blending by adjusting the

DOI http://dx.doi.org/10.1190/segam2015-5858788.1

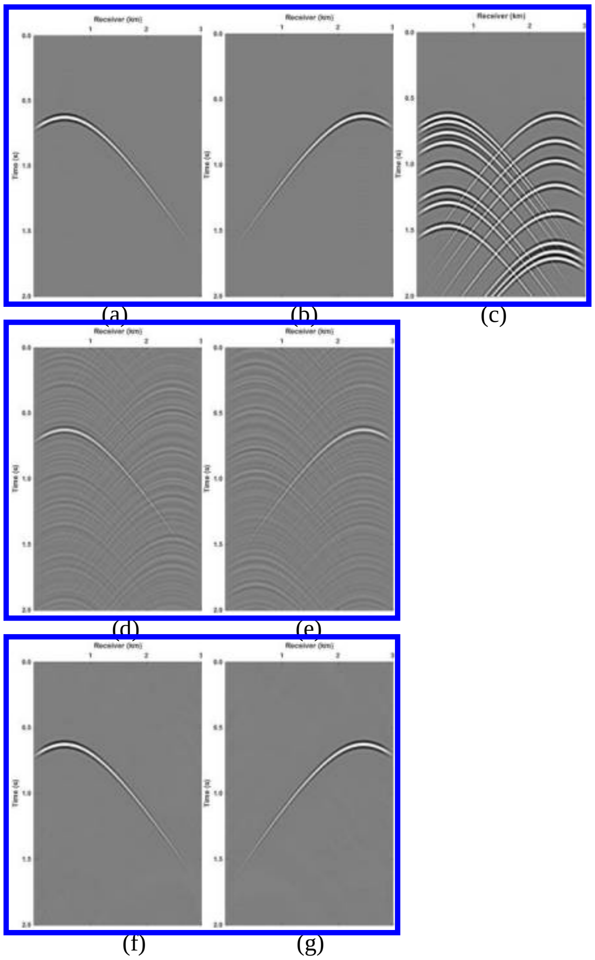


Figure 1: (a) Original response of a left source, (b) original response of a right source, (c) blended shot-repetition data containing two sources that have been fired eight times each (sixteen responses in total), (d)-(e) the pseudo-deblended results, (f)-(g) the deblended results.

blending matrix. The shot-repetition data, $\mathbf{P}'$, can be modelled as:

$$\mathbf{P}' = \mathbf{P}\boldsymbol{\Gamma} , \qquad (1)$$

where $\mathbf{P}$ is the so-called data matrix in the frequency domain (Berkhout, 1982). Each element of $\mathbf{P}$ is a complex-valued number that represents one frequency component of a recorded trace. Each column of $\mathbf{P}$ represents a monochromatic shot gather, and each row represents a monochromatic receiver gather. $\boldsymbol{\Gamma}$ is the blending matrix. Each column of $\boldsymbol{\Gamma}$ corresponds to one blended seismic experiment, and each row of $\boldsymbol{\Gamma}$ corresponds to a source location. As already mentioned, in the case of shot repetition, each source is activated more than once at the same location. As a consequence, each nonzero element of the blending matrix, Γ_{kl}, leads to multiple time delays for the source at location k in blending experiment l. Hence, Γ_{kl} can be written as a sum of phase terms:

$$\Gamma_{kl} = \sum_{n=1}^{N} e^{-j\omega\Delta t_{kl,n}} . \qquad (2)$$

In equation 2, $\Delta t_{kl,n}$ is the time shift corresponding to the n^{th} activation time of the source. As previously stated, in this abstract examples are shown with N=8 and two nonzero elements in each column of $\boldsymbol{\Gamma}$. Figure 1c shows a simple example of shot-repetition data, where the two blended sources (Figures 1a and 1b) are coded with near-orthogonal sequences in shot-repetition fashion.

Deblending in the case of shot repetition

The deblending of shot-repetition data aims at retrieving individual shots as if they were acquired conventionally. The deblending process is an underdetermined inverse problem, because the blended data matrix, $\mathbf{P}'$, has fewer columns than $\mathbf{P}$. To solve this problem we can find a least-squares solution and drive it closer to reality by introducing additional physical constraints.

A weighted least-squares solution of the inverse problem is obtained by pseudo-deblending. The pseudo-deblending can be formulated as:

$$\mathbf{P}_{\mathrm{ps}} = \mathbf{P}'\boldsymbol{\Gamma}^{+} , \qquad (3)$$

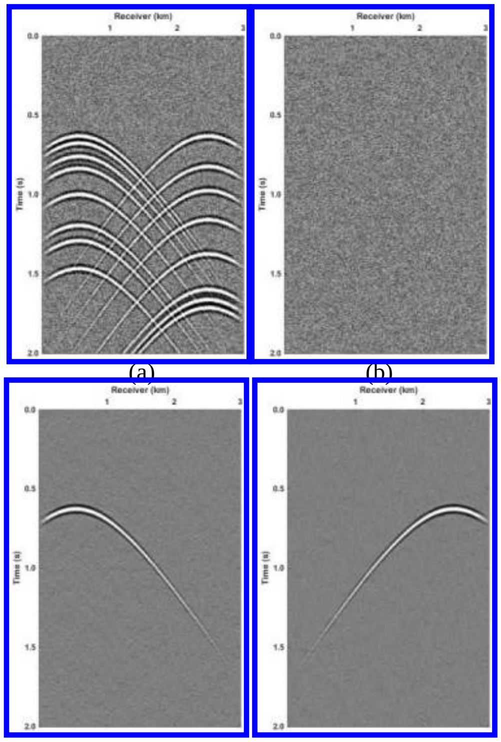
$$\boldsymbol{\Gamma}^{+} = (\boldsymbol{\Gamma}^{\mathrm{H}}\boldsymbol{\Gamma})^{-1}\boldsymbol{\Gamma}^{\mathrm{H}} , \qquad (4)$$

where $\boldsymbol{\Gamma}^{+}$ is the generalized pseudoinverse of $\boldsymbol{\Gamma}$. Note that $\boldsymbol{\Gamma}^{\mathrm{H}}\boldsymbol{\Gamma}$ is a diagonal matrix.

Figure 1d and 1e show the two shot gathers after pseudo-deblending, where the signals are strengthened by a factor of eight compared with the noise. This signal enhancement is due to the poorly correlated source codes that has a spiky autocorrelation function and small cross-correlation values. Our deblending method relies on this signal enhancement in the pseudo-deblended data, and uses an iterative estimation and subtraction scheme. The iterative process starts by applying a threshold to the pseudo-deblended data. The thresholded result is used to compute an estimate of the noise, which is subtracted from the pseudo-deblended data. The outcome is a pseudo-deblended data set with less

DOI http://dx.doi.org/10.1190/segam2015-5858788.1

interfering energy, which will be the input for the next iteration.



(a) (b)

(c) (d)

Figure 2: (a) Blended data with random noise ,(b) random background noise applied to the blended data, (c)-(d) deblended data.

The results (Figure 1f and 1g) are obtained after deblending the shot-repetition data in Figure 1c. It is clearly visible that the deblended shots are near-perfect compared with the original shots. The deblended results have an S/N ratio of 40.9 dB. Comparing with the S/N ratio of the blended data, -11.8 dB, the deblending algorithm achieved an improvement of 52.7 dB.

Improved S/N ratio

Besides a higher data quality with better economics, blended acquisition improves the S/N ratio (Berkhout and Blacquière, 2013). In the case of shot repetition, more shots are induced in one blended experiment and therefore more source energy is sent into the subsurface while the background noise stays the same. The signal-to-background-noise ratio in shot-repetition data is more favourable compared with conventional data or regularly blended data without repetition. Shot-repetition data with random background noise (Figure 2a and 2b) is deblended, yielding the deblended shot gathers shown in Figure 2c and 2d. It is clear that the level of the residual noise in the deblended results have been reduced compared with the initial background noise.

Theoretically the S/N ratio in the deblended data increases by a factor of $\sqrt{NM}$ compared with the S/N ratio in regularly blended data, where N is the number of repeated shots at one source location and M is the blending factor. It is remarked that the residual noise in the above example has been reduced by 11.8 dB, which corresponds to a factor of 3.89. This value is approximately equal to the square root of 16, being the product of N=8 and M=2.

Example on field data

To test the performance of deblending in the case of shot repetition in a realistic setting, we applied the method to a numerically blended field dataset. This gives the advantage that the ‘truth’ is known. The original field data acquired at the North Sea has a temporal and a spatial sampling interval of 4 ms and 12.5 m, respectively. The raw seismic data was pre-processed and rearranged from a 3D dataset to a 2D split-spread dataset. Note that the method would work equally well on the 3D marine geometry data. The pre-processed field data was numerically blended in a shot-repetition fashion, with each source deployed eight times (Figure 3a).

After applying our deblending algorithm, the final results are obtained. It is emphasized again that the algorithm works on individual blended shot gathers. A deblended shot is plotted in Figure 3b and the original shot is plotted in Figure 3c. The strong early events from 0.0 s to 1.2 s are very well resolved. The weak flat reflections in the deep region from 2.0 s to 3.0 s are quite well delineated. The deblending error is plotted in Figure 3d. The S/N ratio of the deblended data is 9.1 dB; compared with the S/N ratio of shot-repetition data (-11.8 dB), an improvement of 20.8 dB was obtained.

Discussion

The main advantage of shot repetition is that the deblending is independent of the source sampling. Because we make use of the forward model of source blending, we can easily combine shot-repetition codes with other blending codes, e.g. the random time delays to the blended inline sources in the method of Mahdad et al. (2011). When the source sampling is sufficient, the additional constraint in domains such as common-receiver domain, will help separating the signal energy from the interfering energy in deblending.

Another benefit of using shot repetition is that it can help reduce the uncorrelated noise. Despite of the attenuation of incoherent random noise that has been discussed previously, the coherent noise, such as the interference from a competitor’s vessel, can also be reduced. The coherent noise can be seen blending together with the signal, except that the blending code of the noise is unknown. The deblending of coherent noise is discussed in Wu (2014).

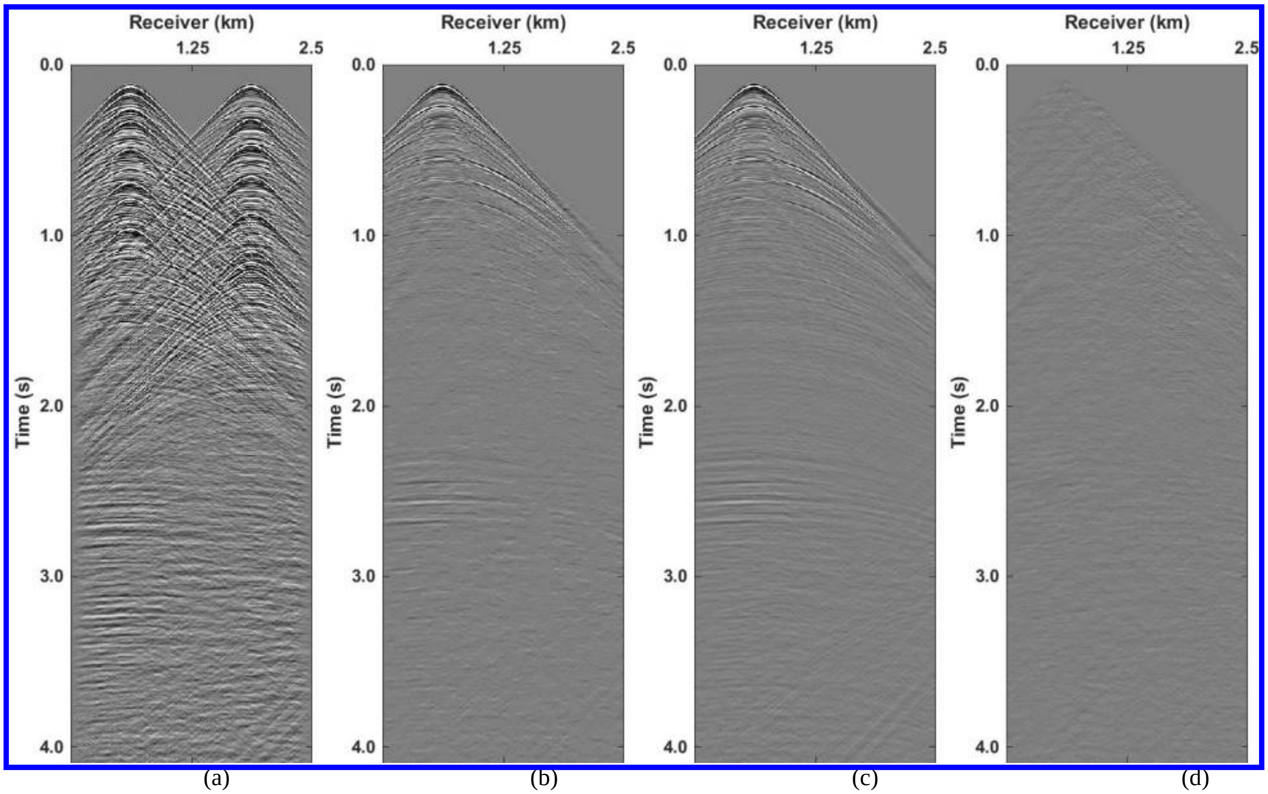
The shot-repetition codes for source blending should be designed such that the sources at different locations are uncorrelated to each other. Besides this criterion, the repeated source energy can be designed intentionally to distribute in non-physical areas, such as the area above the water bottom reflection, or the areas with low interest.

Conclusions

Shot repetition, an alternative approach for source encoding in blended marine acquisition, allows deblending to be carried out per blended shot gather. Deblending in the case of shot repetition uses an iterative estimation and subtraction scheme. This method does not have any restrictions on source spacing. Synthetic data examples show that blending in a shot-repetition fashion enhances the S/N ratio. Initial trials on numerically blended field data show promising results.

Acknowledgements

We would like to acknowledge the members of the DELPHI consortium at TU Delft for their support as well as PGS for the permission to publish the field data.



(a) (b) (c) (d)

Figure 3: (a) A shot gather of numerically blended field data, (b) the deblended left shot, (c) the original left shot, (d) the deblending error.

DOI http://dx.doi.org/10.1190/segam2015-5858788.1

EDITED REFERENCES

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REFERENCES

Abma, R., and A. Ross, 2013, Popcorn shooting: Sparse inversion and the distribution of airgun array energy over time: 83rd Annual International Meeting, SEG, Expanded Abstracts, 31–35, doi: 10.1190/segam2013-0592.1.

Barbier, M. G., and J. R. Viallix, 1973, Sosie: A new tool for marine seismology: Geophysics, **38**, 673–683. http://dx.doi.org/10.1190/1.1440366.

Berkhout, A. J., 1982, Seismic migration, imaging of acoustic energy by wavefield extrapolation: Theoretical aspects: Elsevier.

Berkhout, A. J., 2008, Changing the mindset in seismic acquisition: The Leading Edge, **27**, 924–938. http://dx.doi.org/10.1190/1.2954035.

Berkhout, A. J., and G. Blacquiere, 2014, Combining deblending with source deghosting: Presented at the 76th Annual International Conference and Exhibition, EAGE.

Long, A. S., E. von Abendorff, M. Purves, J. Norris, and A. Moritz, 2013, Simultaneous long offset towed streamer seismic acquisition: 75th Annual International Conference and Exhibition, EAGE, Extended Abstracts, http://dx.doi.org/10.3997/2214-4609.20130377.

Mahdad, A., P. Doulgeris, and G. Blacquiere, 2011, Separation of blended data by iterative estimation and subtraction of blending interference noise: Geophysics, **76**, no. 3, Q9–Q17. http://dx.doi.org/10.1190/1.3556597.

Mueller, M. B., J. O. A. Robertsson, and D. F. Halliday, 2014, Simultaneous source separation using encoded source sequences: 76th Annual International Conference and Exhibition, EAGE, Extended Abstracts, http://dx.doi.org/10.3997/2214-4609.20141457.

Vaage, S. T., 2002, Method and system for acquiring marine seismic data by using multiple sources: U. S. Patent 6,906,981.

Wu, S., 2014, Seismic deblending by shot repetition: Master's thesis, Delft University of Technology.

DOI http://dx.doi.org/10.1190/segam2015-5858788.1