

The concept of double blending: Combining incoherent shooting with incoherent sensing

A. J. Berkhout¹, G. Blacquière¹, and D. J. Verschuur¹

ABSTRACT

Seismic surveys are designed so that the time interval between shots is sufficiently large to avoid temporal overlap between records. To economize on survey time, the current compromise is to keep the number of shots to an acceptable minimum. The result is a poorly sampled source domain. We propose to abandon the condition of nonoverlapping shot records to allow densely sampled, wide-azimuth source distributions (source blending). The rationale is that interpolation is much harder than separation. Source blending has significant implications for quality (source density) and economics (survey time). In addition to source blending, detector blending is introduced by which every channel records a superposition of detected signals, each with its own particular code. With detector blending, many more detectors can be used for the same number of recording channels. This is particularly beneficial when the number of detectors is very large (mass sensing) or the number of channels is limited (wireless recording). The concept of double blending is defined as the case in which both source blending and detector blending are applied. Double blending allows a significant trace-compression factor during acquisition.

INTRODUCTION

The concept of simultaneous sources is well known from vibroseis acquisition. To reduce survey time, methods for simultaneous shooting have been developed based on signal coding, so that in the preprocessing the interfering source responses can be separated. [Bagaini \(2006\)](#) gives an overview of the various simultaneous vibroseis sweep methods. [Ikelle \(2007\)](#) discusses coding and decoding. In marine seismics, the use of impulsive sources does not allow for coding. [Beasley et al. \(1998\)](#) propose to fire impulsive sources simultaneously at different locations. [Vaage \(2002\)](#) and [Stefani et al.](#)

[\(2007\)](#) elaborate on this concept and use small random time delays as well: near simultaneous shooting. In a special section on seismic acquisition in the July 2008 issue of *THE LEADING EDGE*, several papers on the subject can be found for further reading ([Beasley, 2008](#); [Hampson et al., 2008](#)). In addition, a special session at the 2008 SEG meeting was dedicated to simultaneous sources ([Moore et al., 2008](#); [Howe et al., 2008](#)).

The concept of simultaneous shooting is applicable not only in the source space, but also in the detector space. For instance, the use of traditional detector patterns in the field (also known as group forming) can be considered as an application of “simultaneous detection.”

In this paper, the method of (near) simultaneous shooting and simultaneous detection is extended to the more general system concept of double blended acquisition: source blending along with detector blending. Source blending stands for continuous recording of multisource responses that overlap in time. The multisource properties are characterized by the source locations (offsets, azimuths) and time shifts. Delay times might be large (as long as seconds), and additional encoding of source signatures is optional. For more information on source blending, the reader is referred to [Berkhout \(2008\)](#).

Detector blending stands for continuous recording of the responses sensed by multidetector configurations. In such configurations, the detected signals of various detectors are summed after they have been given a particular delay. The multidetector properties are characterized by the detector locations and delay times. Again, delay times might be large (as long as seconds), and additional encoding of detector signals is optional.

Double blended acquisition means that both source blending and detector blending are applied. A theoretical framework is proposed that describes double blending as a multiplication by matrix operators. Based on this forward model of double-blended 3D seismic data, different options for processing (preprocessing) such data can be developed.

Manuscript received by the Editor 27 January 2009; revised manuscript received 16 March 2009; published online 11 June 2009.

¹Delft University of Technology, Delphi Consortium, Delft, The Netherlands. E-mail: A.J.Berkhout@tudelft.nl; G.Blacquiere@tudelft.nl; D.J.Verschuur@tudelft.nl.

© 2009 Society of Exploration Geophysicists. All rights reserved.

THEORY

Systems representation of seismic data

A seismic data set can be arranged conveniently with the aid of the so-called data matrix \mathbf{P} , where a column represents a shot record and a row represents a detector gather. In the frequency domain, element \mathbf{P}_{ij} is a complex-valued scalar, representing one temporal frequency component of the seismic trace related to source position j and detector position i . At system level, the model of 3D seismic reflection measurements can be written as (Berkhout, 1982)

$$\mathbf{P}(z_d, z_s) = \mathbf{D}(z_d) \mathbf{X}(z_d, z_s) \mathbf{S}(z_s), \quad (1)$$

where z_d and z_s represent the depth levels of the detectors and sources, respectively. They might be a function of the lateral coordinates x and y . Here, $\mathbf{S}(z_s)$ is the source matrix, containing amplitude and phase of the source wavelet(s) for one frequency component. Each column of $\mathbf{S}(z_s)$ represents a source (array) as used in the field. The expression $\mathbf{X}(z_d, z_s)$ is the multidimensional transfer function of the subsurface and $\mathbf{D}(z_d)$ is the detector matrix, containing the detector characteristics for one frequency component. Each row of $\mathbf{D}(z_d)$ represents a detector (array).

Equation 1 shows the importance of proper acquisition: subsurface operator \mathbf{X} is embedded by source operator \mathbf{S} and detector operator \mathbf{D} , which together define the acquisition geometry. Sparse \mathbf{S} and \mathbf{D} matrices will cause significant information losses when moving from \mathbf{X} to \mathbf{P} .

The concept of detector blending

The concept of blending is applicable not only in the source space, where it is called source blending, but it can be applied also in the detector space: detector blending. In the situation of source blending, acquisition is carried out with relatively small differential firing times between consecutive shots, causing shot records to overlap in time (Berkhout, 2008). We call this type of seismic emission shooting with incoherent arrays or, in short, incoherent shooting. This is particularly beneficial in economic multiazimuth acquisition and economic borehole seismics. Similarly, in the situation of detector blending, the signals from detectors at different locations are time shifted, each with its own shift, and then summed to form one channel signal. As a consequence, the number of detectors can be increased strongly for a given number of recording channels. This is

particularly beneficial if the number of recording channels is an issue, as in wireless acquisition where bandwidth is limited.

Alternatively, the same number of detectors can be deployed with a reduced number of recording channels, or any mixture of both approaches is possible. If one blended detector array consists of 25 detectors, for example, then one channel will record 25 superimposed traces. Note that in the case of traditional field arrays, there is no delay between the detectors prior to summation. Hence, the signals are coherently summed, having the detrimental effect that the high-angle waves are suppressed. In the case of detector blending, however, the aim in the acquisition design is to sum incoherently, aiming at preservation of the full spatial bandwidth. We call this type of seismic detection sensing with incoherent arrays or, in short, incoherent sensing.

Detector blending can be formulated as

$$\mathbf{P}'(z_d, z_s) = \mathbf{\Gamma}_D(z_d) \mathbf{D}(z_d) \mathbf{X}(z_d, z_s) \mathbf{S}(z_s), \quad (2)$$

where superscript \prime is used to indicate detector blending. Matrix $\mathbf{\Gamma}_D$ is called the detector-blending matrix. Each row contains the information of one blended detector array, i.e., the time shifts (or any more complex code) of the involved detectors and their location. The codes are defined by complex-valued scalars for the corresponding frequency, whereas the involved detector locations are indicated by the positions of these scalars in the row.

From equations 1 and 2 it follows that, at least in principle, deblending can be described by matrix inversion:

$$\mathbf{P}(z_d, z_s) = \mathbf{\Gamma}_D^{-1}(z_d) \mathbf{P}'(z_d, z_s). \quad (3)$$

In practice, however, the number of rows of $\mathbf{\Gamma}_D$ will be smaller than the number of columns. In that case, it cannot be inverted readily. However, the least-squares formalism offers an approximate inverse, $\mathbf{\Gamma}_D^H (\mathbf{\Gamma}_D \mathbf{\Gamma}_D^H)^{-1}$, where superscript H denotes the complex conjugate transpose. This expression can be approximated further by a scaled version of $\mathbf{\Gamma}_D^H$. We call this simple process pseudodeblending. It means that only the time shifts are compensated for.

The concept of detector blending is illustrated in Figure 1 with a synthetic data set containing 400 shot records with 400 detectors each. The detectors are located on a straight line at the surface, with a spatial sampling interval of 15 m. For the source locations, the same applies. The modeling algorithm is an acoustic finite-difference method, and the subsurface model is horizontally layered. Incoherent sensing was modeled with five detectors per blended detector array, each with its own time shift. The result is a data set containing 80

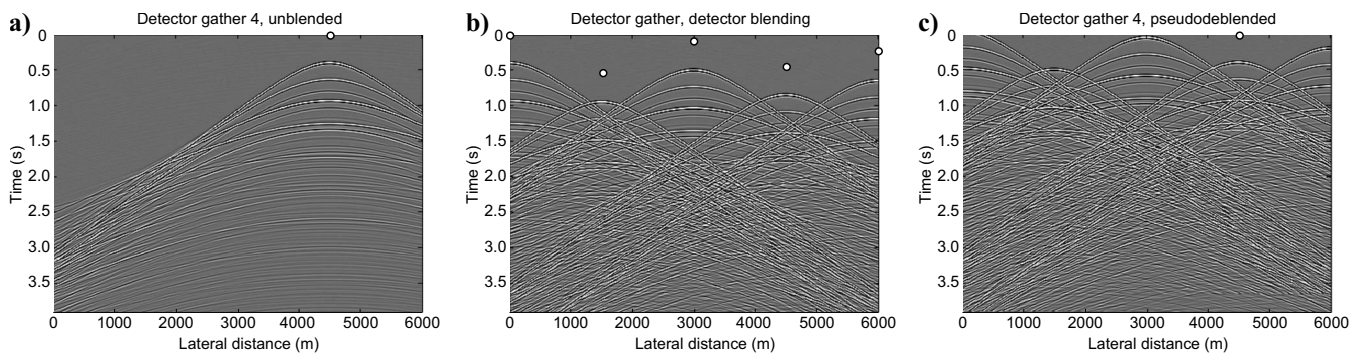


Figure 1. (a) Unblended detector gather with detector at $x = 4500$ m. (b) Blended detector gather recorded by an incoherent array of five detectors with random delays of 0, 0.55, 0.10, 0.45, and 0.25 s, and located at $x = 0, 1500, 3000, 4500,$ and 6000 m, respectively; the white dots indicate the detector delays and the detector positions. (c) Pseudodeblended detector gather for the detector at location $x = 4500$ m.

blended detector gathers with 400 traces each (corresponding to the shots). In the pseudodeblended result, the original shot record can be recognized. The energy resulting from the other shots we call interference noise.

The concept of double blending

Blending in the detector space can be combined with blending in the source space. This leads to the concept of double blending:

$$\mathbf{P}''(z_d, z_s) = \mathbf{\Gamma}_D(z_d)\mathbf{D}(z_d) \times \mathbf{X}(z_d, z_s)\mathbf{S}(z_s)\mathbf{\Gamma}_S(z_s), \quad (4)$$

where the double superscript '' represents double blending and $\mathbf{\Gamma}_S$ is the source blending matrix. Each column of $\mathbf{\Gamma}_S$ contains the information of one blended source array (Berkhout, 2008). In the frequency domain, element \mathbf{P}''_{ij} represents the response of blended source array j as measured by blended detector array i .

The same data set is used to illustrate the double blending process; see Figure 2. Double blending has been modeled using four sources per blended source array and five detectors per blended detector array. The result contains 100 blended shot records with 80 blended traces each. Compare this with the input data containing 400 shots with 400 traces each. This means a considerable trace-compression factor. Notice the incoherent character of the double-blended shot record. This is because of the relatively large and irregular time delays that have been chosen for the source and detector blending with the aim of preserving the full spatial bandwidth. Notice the power of pseudodeblending in Figure 2b, where coherent signal now is clearly visible.

Our research already has shown that the distance between sources/detectors should be inversely related to the time shifts. This is used in our design process, which is based on the spatial bandwidth properties of blending operators $\mathbf{\Gamma}_S$ and $\mathbf{\Gamma}_D$, as well as on the focusing properties of the involved incoherent wavefields.

To demonstrate the essential role of time shifts in the coding, the power of time reshifting (as occurs in pseudodeblending) is shown by applying shot-record migration to pseudodeblended data. For this example, acoustic finite-difference data have been generated for an inhomogeneous subsurface model, consisting of 90 shot records with 360 traces each. The blending factor for both the sources and the detectors is five, resulting in 18 blended shot records of 72 blended traces each.

Figure 3 shows the results of migrating the pseudodeblended data in the cases of, respectively, no blending (reference case), source blending, detector blending, and double blending. The results are surprisingly good, despite the fact that

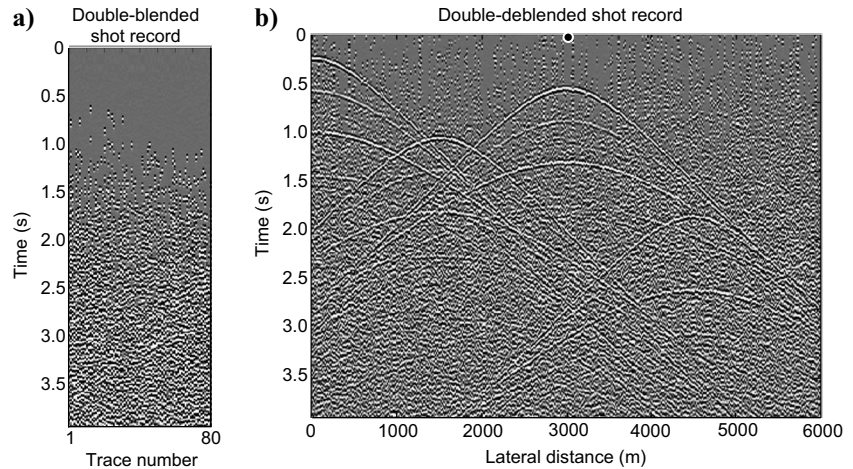


Figure 2. Double blending: from 400 shot records with 400 traces each to 100 shot records with 80 traces each (trace-compression factor 20). The blended source array consists of four sources and the blended detector array consists of five detectors. (a) Double-blended shot record (80 traces). Note the high degree of incoherence. (b) Double pseudodeblended shot record (400 traces) with source position at $x = 1500$ m, indicated by the black dot. The large impact of the pseudodeblending process is very clear.

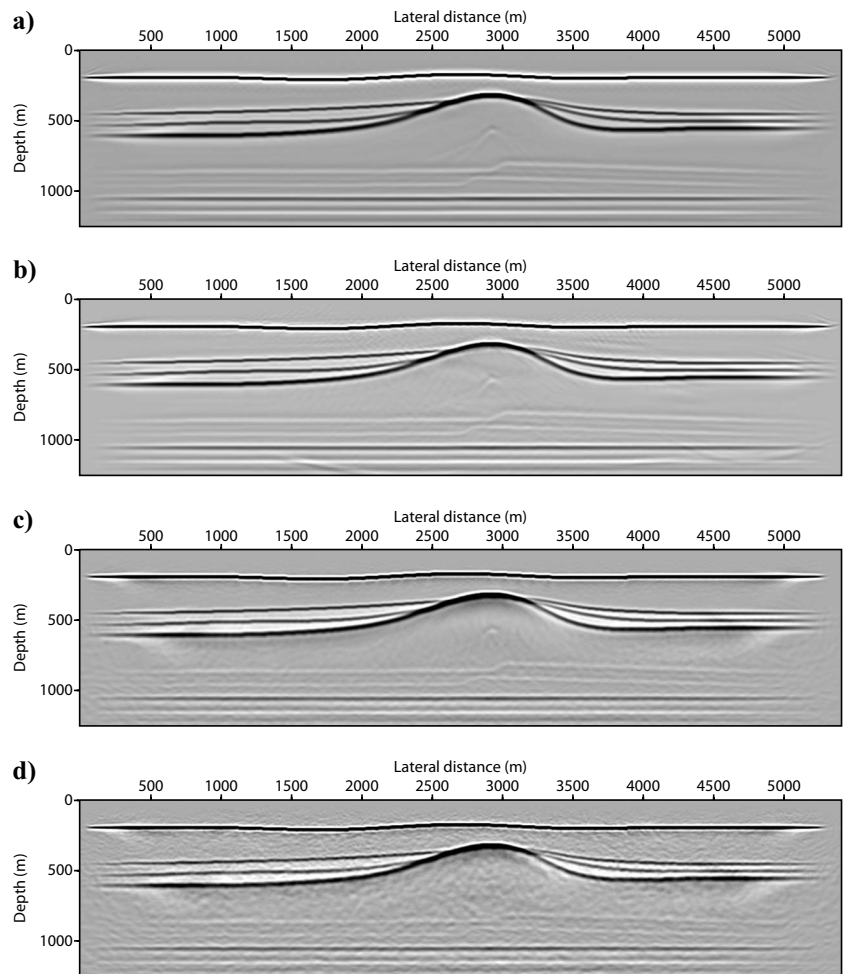


Figure 3. Migration results after pseudodeblending. (a) No blending (90*360). (b) Source blending (18*360). (c) Detector blending (90*72). (d) Double blending (18*72).

time shifts were the only blending and deblending parameters. Obviously, the double-focusing process in migration, i.e., focusing in detection and focusing in emission (van Veldhuizen et al., 2008), is a very effective attenuator of interference noise. This is what we also see in the design process. The new challenge, however, is to aim for new processing solutions that do not require a deblending preprocessing step: from coherent to incoherent wavefield processing.

CONCLUSIONS

- 1) It is proposed to replace current seismic acquisition methods (discontinuous recording, zero overlap in time) by a blended alternative (continuous recording, significant overlap in time). It is believed that the interpolation of missing shot records in conventional acquisition is much harder to accomplish than the separation of overlapping shot records in blended acquisition.
- 2) The blending concept can be applied also in the detector space. It provides a new view on traditional detector arrays and creates the flexibility to retrieve significantly more detector signals for a given number of acquisition channels. The combination of blended sources and blended detectors — double blending — opens the opportunity for a large trace-compression factor during acquisition.
- 3) With the focus on quality, the concept of blended acquisition allows significantly denser spatial sampling, a larger aperture, and a much wider range of azimuths for the same number of channels and the same survey time. These properties could lead to the next principal step of improvement in seismic imaging quality.
- 4) With the focus on economics, the concept of blending allows significantly fewer channels and shorter survey times for the same amount of seismic traces. These properties are particularly valuable for those situations in which field channels are ex-

pensive and small acquisition time windows dominate because of safety, environmental, or economic restrictions.

- 5) After deblending, existing processing schemes can be used. Our migration example shows, for instance, that the double-focusing process in migration is a very effective attenuator of interference noise. The new challenge, however, is to aim for new solutions that do not require a deblending preprocessing step: from coherent to incoherent wavefield processing.

REFERENCES

- Bagaini, C., 2006, Overview of simultaneous vibroseis acquisition methods: 76th Annual International Meeting, SEG, Expanded Abstracts, 70–74.
- Beasley, C. J., 2008, A new look at marine simultaneous sources: *The Leading Edge*, **27**, 914–917.
- Beasley, C. J., R. E. Chambers, and Z. Jiang, 1998, A new look at simultaneous sources: 68th Annual International Meeting, SEG, Expanded Abstracts, 133–135.
- Berkhout, A. J., 1982, *Seismic migration, imaging of acoustic energy by wave field extrapolation: A — Theoretical aspects*: Elsevier Science.
- , 2008, Changing the mindset in seismic data acquisition: *The Leading Edge*, **27**, 924–938.
- Hampson, G., J. Stefani, and F. Herkenhoff, 2008, Acquisition using simultaneous sources: *The Leading Edge*, **27**, 918–923.
- Howe, D., M. Foster, T. Allen, B. Taylor, and I. Jack, 2008, Independent simultaneous sweeping — A method to increase the productivity of land seismic crews: 78th Annual International Meeting, SEG, Expanded Abstracts, 2826–2830.
- Ikelle, L., 2007, Coding and decoding: Seismic data modeling, acquisition, and processing: 77th Annual International Meeting, SEG, Expanded Abstracts, 66–70.
- Moore, I., B. Dragoset, T. Ommundsen, D. Wilson, C. Ward, and D. Eke, 2008, Simultaneous source separation using dithered sources: 78th Annual International Meeting, SEG, Expanded Abstracts, 2806–2810.
- Stefani, J., G. Hampson, and F. Herkenhoff, 2007, Acquisition using simultaneous sources: 69th Conference & Exhibition, EAGE, Extended Abstracts, B006.
- Vaage, S. T., 2002, Method and system for acquiring marine seismic data using multiple seismic sources: U.S. Patent 6 906 981.
- van Veldhuizen E. J., G. Blacquièrè, and A. J. Berkhout, 2008, Acquisition geometry analysis in complex 3D media: *Geophysics*, **73**, no. 5, Q43–Q58.