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**DOI**
10.3997/2214-4609.201600839

**Publication date**
2016

**Document Version**
Final published version

**Published in**
78th EAGE Conference and Exhibition 2016, Vienna, Austria

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# Seismic Acquisition with Dispersed Source Arrays - Imaging Including Internal Multiples and Source Ghost Reflections

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## SUMMARY

A seismic acquisition method is proposed that involves the exploitation of inhomogeneous sources. The constraint of employing only identical units can be abandoned. We suggest to replace (or reinforce) traditional broadband sources with narrow(er)band devices, together representing a dispersed source array (DSA). The whole inhomogeneous ensemble of sources incorporated to the arrays is required to cover the entire temporal and spatial bandwidth of interest. The DSA concept can be an important step towards the robotization of the seismic acquisition process and an improved operational flexibility. In addition, narrow band source design can be better optimized, no compromise between the emission efficiency around the limits of the bandwidth of interest is requested. Furthermore specific attention can be addressed to choose source depths and spatial sampling intervals that are optimum for particular devices. Valid and encouraging numerical migration results are shown.

## Introduction

The constraint of employing only identical sources during seismic surveys can be abandoned. Following the guidelines drawn by Berkhout (2012), we suggest to replace (or reinforce) traditional broadband units with narrow(er)band devices, together representing a Dispersed Source Array (DSA).
The whole inhomogeneous ensemble of sources incorporated to the array is required to cover the entire temporal and spatial bandwidth of interest. This concept can be an important step towards the robotization of the seismic acquisition process and an improved operational flexibility, which make DSA survey systems particularly suitable for blended acquisitions. Addressing specific attention to the design of different narrowband source units might drastically improve their signal emission properties. Modern loudspeaker systems are based on the same key concept and their improved performances are demonstrated (Davis and Davis, 1997).
Moreover, since the sampling requirements depend on the transmitted frequencies, the needed number of sources dedicated to the lower frequencies is relatively small. Furthermore, except for the very low frequencies of seismic interest, the conventional sources are significantly louder and bigger than required (see for example Laws et al., 2008; Fontana and Zickerman, 2010). Higher frequency devices could be smaller, less powerful, and therefore more suitable to comply with the emerging concerns and regulations on sea life protection (Popper and Hawkins, 2012).
Extra benefits arise if we look at the source ghost issue. Each source type can be placed at the optimum depth below the water surface, i.e. at $z_s = \lambda_c/4$, one quarter of its central frequency wavelength $\lambda_c$. Ghost destructive interference and notches are then largely avoided.
The employment of narrowband or monochromatic low-frequency sources in seismic acquisition has also been proposed by Dellinger et al. (2012), mainly as a reinforcement for conventional broadband acquisition. On the other hand, an interesting first attempt of DSA land data acquisition and inversion (FWI-based) has been successfully carried on and presented by Kim and Tsingas (2014). Nevertheless, the main focus of the study presented hereafter is on marine environment. Valid and encouraging numerical migration outputs are shown.

## Method and Theory

In this section, wave field extrapolation based modeling will be briefly discussed by means of the $\mathbf{W}^-\mathbf{R}\mathbf{W}^+$ model proposed by Berkhout (1982) and extended to the description of a blended DSA acquisition system. Matrices $\mathbf{W}^-$, $\mathbf{W}^+$ and $\mathbf{R}$ refer to the up- and downward propagation matrices and the reflectivity matrix, respectively. This method gives the possibility to describe seismic field measurements and numerical simulations using a compact and advantageous notation.
The seismic data is stored in the so called data matrix $\mathbf{P}(z_0,z_0)$. Each column of $\mathbf{P}(z_0,z_0)$ represents a different shot record while each row of $\mathbf{P}(z_0,z_0)$ describes a receiver gather. In the space-frequency domain, each monochromatic component of the primary wave field can be mathematically expressed, for a stationary geometry, as

$$\mathbf{P}(z_0,z_0) = \mathbf{D}(z_0)\left[\sum_{m=1}^{M}\mathbf{W}^-(z_0,z_m)\mathbf{R}(z_m,z_m)\mathbf{W}^+(z_m,z_0)\right]\mathbf{S}(z_0) \tag{1}$$

For this particular case, the wave field is both generated and recorded at the surface level $z_0$. Such operators have the following meaning:

- $\mathbf{S}(z_0)$ is the source matrix. It contains amplitude and phase information about the source wave field at the frequency under consideration. Key information about the spectral properties of the different DSA sources is therefore enclosed here. Each column represents one source (array). Each row corresponds to a different spatial coordinate.
- $\mathbf{W}^+(z_m,z_0)$ is the forward, downgoing wave field propagation matrix. Each column contains a discretized Green's function describing the wave propagation from one lateral location in space at

the surface depth level $z_0$ to all grid points at depth level $z_m$.

- $\mathbf{R}(z_m, z_m)$ is the reflectivity matrix, describing the (angle-dependent) scattering occurring at depth level $z_m$. In other words, it specifies how the incident wave field is converted into the reflected wave field.
- $\mathbf{W}^-(z_0, z_m)$ is the forward, upgoing wave field propagation matrix. Each column contains a discretized Green's function describing the wave propagation from one lateral location in space at depth level $z_m$ to all grid points at the surface depth level $z_0$.
- $\mathbf{D}(z_0)$ is the detector matrix. It contains amplitude and phase information about the detectors at the frequency under consideration. Each row represents one detector (array). Each column corresponds to a different spatial coordinate.

Within this framework, it is possible to introduce the concept of blending by defining the so called blending matrix $\Gamma(z_0)$. The columns of $\Gamma(z_0)$ define the details about the linear combination of the different sources of the array to be employed for the correspondent blended shot. The elements of $\Gamma(z_0)$, in case of simple time delays, are given by $\gamma_{ik}(z_0) = e^{-j\omega\tau_{ik}}$, where $\tau_{ik}$ determines the time delay relative to the $i$-th source for the $k$-th experiments.
The blended source matrix $\mathbf{S}'(z_0)$ and data matrix $\mathbf{P}'(z_0, z_0)$ are therefore defined by

$$\mathbf{S}'(z_0) = \mathbf{S}(z_0)\Gamma(z_0) \qquad \textit{and} \qquad \mathbf{P}'(z_0, z_0) = \mathbf{P}(z_0, z_0)\Gamma(z_0) \tag{2}$$

Using the $\mathbf{W}^-\mathbf{R}\mathbf{W}^+$ model, it is also possible to mathematically formulate a convenient expression for the seismic data including multiple scattering. The effect of surface and internal multiples can be added iteratively. More general formulations of Equation 1 and Equation 2 would be

$$\mathbf{P}(z_0, z_0) = \mathbf{D}(z_0)\mathbf{X}(z_0, z_0)\mathbf{S}(z_0) \qquad \textit{and} \qquad \mathbf{P}'(z_0, z_0) = \mathbf{D}(z_0)\mathbf{X}(z_0, z_0)\mathbf{S}'(z_0) \tag{3}$$

where $\mathbf{X}(z_0, z_0)$ is the so called earth transfer function and may also include all multiples in the extrapolation scheme. For more detailed information on how to incorporate the multiples in the modeling scheme, the reader is referred to Berkhout (2014a).

**Examples**

In this section, we will demonstrate the feasibility of the DSA acquisition method with numerical examples of forward modeling and migration.
To illustrate the concept, four different source unit types are used: *ultralow*- (2 Hz - 6 Hz), *low*- (5 Hz - 15 Hz), *mid*- (10 Hz - 30 Hz) and *high*-frequency sources (20 Hz - 60 Hz). Note that each source among the selected ones spans a frequency bandwidth corresponding to the same number of octaves. In such situation, given bandwidths are partially overlapping. Correspondent examples of acoustic energy propagation in a homogeneous medium are presented in Figure 1.
Migration has been performed on the datasets using a JMI (Joint Migration Inversion) algorithm. It aims at estimating a kinematically accurate velocity model along with a valid structural image based on reflection data including primaries and internal multiples. For this particular application, surface related multiples are considered to have been removed during the processing steps. The reader is referred to Staal and Verschuur (2013) and Berkhout (2014b) for further details.
The reflectivity and velocity models we used as reference are shown in Figure 2a and 2b. The marine subsurface profile is featured by a horizontal pack of layers, representing the target area, and a salt structure that serves as a strong internal multiple generator. Two different datasets corresponding respectively to a conventional broadband and a DSA acquisition scheme have been simulated. In both cases each source involved has been placed at the optimum depth below the water surface, i.e. at $z_s = \lambda_c/4$. No deghosting has been performed on the source side.

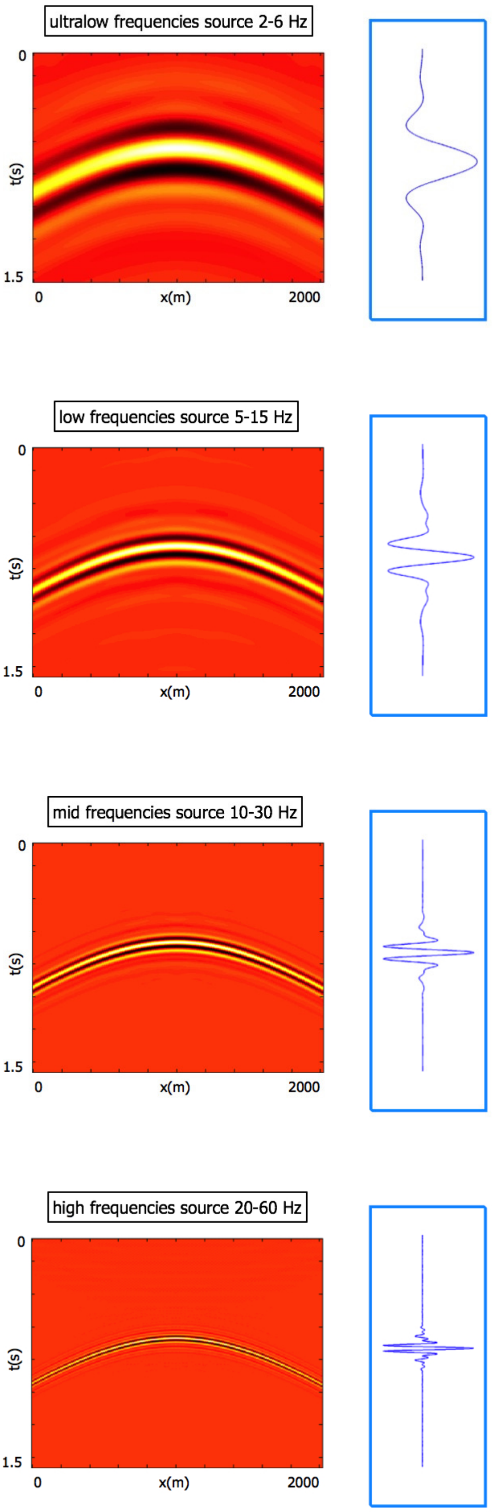


***Figure 1*** *Examples of DSA acoustic energy propagation in a homogeneous medium.*

For the first simulation, the data have been modeled considering a regular source spacing of 100 meters along the surface. Sources have been chosen to be broadband units with a bandwidth ranging from 5 Hz to 60 Hz. The inversion outputs, in terms of reflectivities and velocities, are shown in Figure 2c and 2d.
For the second simulation, a DSA acquisition system has been considered. The data have been modeled considering a regular source spacing of 100 meters along the surface for the high-frequency sources. The spacing has been proportionally decreased in a frequency dependent manner for the other source types: 200 meters for the mid-frequency sources, 400 meters for the low-frequency sources and 1000 meters for the ultralow-frequency sources. The inversion outputs are shown in Figure 2e and 2f.
As expected, the inversion performed on the DSA dataset produces more reliable results compared to the one performed on the broadband dataset. The presence of the ghost reflections is visible in the image correspondent to the broadband result, producing a loss on the resolution around the boundaries of the geological structures. This effect is instead largely attenuated in the DSA case. Furthermore, the ultralow-frequency sources involved in the DSA acquisition allow a better overall estimation of the velocities.

## Conclusions

Applying the DSA concept, it is possible to make some fundamental improvements by changing the system architecture. The design of narrowband sources, which together cover the total bandwidth of interest, may become significantly simpler. Additionally, the source density could be chosen in a frequency dependent manner. Applying this concept, surveys may be carried out by acquisition systems that are less complex and considerably more flexible than the ones that are used today. Furthermore, the possibility to use tow depths that are optimum for the specific central frequency of narrowband sources gives extra benefits if we look at the source ghost issue. Ghost destructive interference and low frequency attenuation due to shallow tow depths are largely avoided. Interesting and encouraging migration outputs from DSA datasets have already been produced. Moreover, considering the potential significant flexibility that the DSA concept would give to the acquisition system, the design of an optimum blended survey system is a logical next step forward in this framework.

## Acknowledgements

The authors would like to thank the sponsors of the Delphi consortium for the stimulating discussions during the Delphi meetings and the continuing financial support.

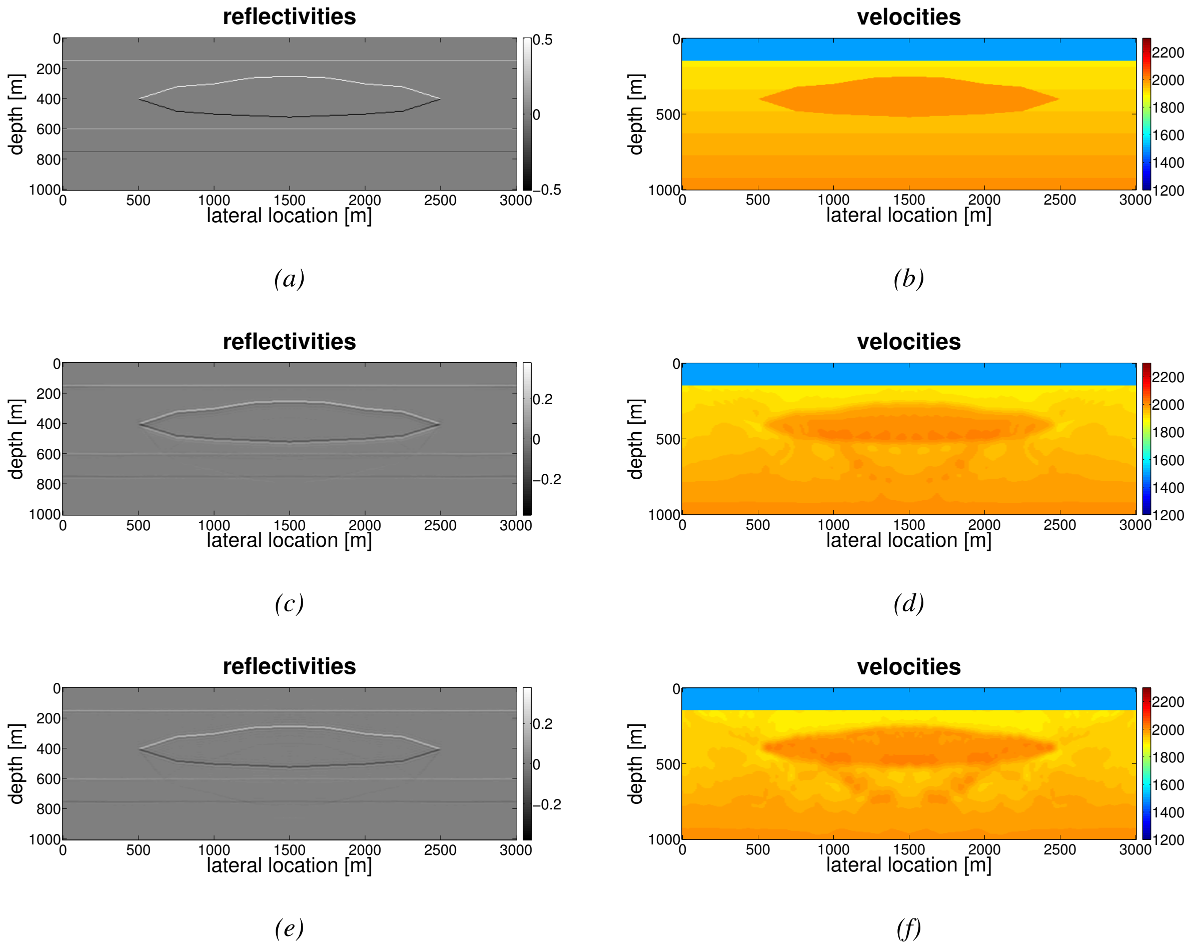


***Figure 2*** *Reference model and JMI results. (a) True reflectivities. (b) True velocities. (c) Estimated reflectivities from Broadband data. (d) Estimated velocities from Broadband data. (e) Estimated reflectivities from DSA data.(f) Estimated velocities from DSA data.*

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