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# Blended acquisition with dispersed source arrays

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## ABSTRACT

Blended source arrays are historically configured with equal source units, such as broadband vibrators (land) and broadband air-gun arrays (marine). I refer to this concept as homogeneous blending. I have proposed to extend the blending concept to inhomogeneous blending, meaning that a blended source array consists of different source units. More specifically, I proposed to replace in blended acquisition the traditional broadband sources by narrowband versions — imagine coded single air guns with different volumes or coded single narrowband vibrators with different central frequencies — together representing a dispersed source array (DSA). Similar to what we see in today's audio systems, the DSA concept allows the design of dedicated narrowband source elements that do not suffer from the low versus high frequency compromise. In addition, the DSA concept opens the possibility to use source depths and spatial sampling intervals that are optimum for the low-, mid-, and high-frequency sources (multiscale shooting grids). DSAs are considered to be an important step in robotizing the seismic acquisition process.

## INTRODUCTION

In traditional seismic surveys, interference between shot records is minimized by choosing the temporal interval and/or the lateral distance between consecutive shots sufficiently large. However, in the concept of simultaneous shooting, shot records do overlap, allowing denser source sampling in a favorable economic way. Denser source sampling takes care of the desired property that each subsurface gridpoint is illuminated by the downgoing source wavefield from a larger number of angles and, therefore, will improve the image quality in terms of signal-to-noise ratio and spatial resolution.

An abundance of references on simultaneous shooting can be found in the seismic literature. Examples of recent publications are Beasley (2008), Berkhout (2008), Berkhout et al. (2009), Howe et al. (2008), and Pecholcs et al. (2010). In blended acquisition, being a special version of simultaneous shooting, the "simultaneous" source wavefield is *incoherent*. Such a physical wavefield is generated by firing a multitude of sources, each source with its own code (such as temporal delay, phase rotation, or pseudorandom maximum length series), together forming a blended source array. Unlike a traditional source array, a blended source array may cover a large spatial area, meaning that one blended source array illuminates subsurface gridpoints from many different angles (Berkhout, 2008). The objective of blended acquisition is to maximize the emission of full-bandwidth, nonaliased, far-field signal energy within a prespecified acquisition time.

In traditional seismic surveys, a single coherent source (array) is used for each shot record. This localized source unit must transmit the full temporal frequency band for a wide range of emission angles. For example, today's seismic vibrators (land) and air-gun arrays (marine) are designed such that they have a large bandwidth, ranging over many octaves. In practice, it requires a lot of effort to successfully produce and operate wideband sources. More important, such source designs are always a compromise from a system engineering as well as a wave transmission point of view. For instance, for the low frequencies on land, a large vibrator baseplate area should be used to improve the far-field to near-field signal energy (less evanescent energy). With a large-size baseplate, however, the baseplate starts to bend at high frequencies and the reaction mass begins to drift out of phase with the baseplate; the result is that the vibrator would not be able to efficiently transmit high frequencies.

I propose that the individual source units in a blended array (1) are not chosen to be equal and (2) do not need to satisfy the wideband requirements. Instead, they may be dedicated narrowband designs with superior emission properties around their central frequency. The ultimate criterion is that the combined incoherent source wavefield has the required temporal and angular spectral properties at each gridpoint in the subsurface.

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## THEORETICAL CONSIDERATIONS

Seismic data can be arranged in data matrix $\mathbf{P}$ (see Figure 1). In the frequency domain, $\mathbf{P}$ represents a frequency slice of the total data volume and one element, $\mathrm{P}_{ij}$, is a complex-valued number, being one frequency component of the trace at detector position $i$ generated by source $j$. In my notation, $\mathbf{P}(z_d, z_s)$ means that the source and detector positions are situated at depth levels $z_s$ and $z_d$, respectively. If we choose for the moment $z_s = z_d = z_0$ (typical for land data), then the model of data matrix $\mathbf{P}(z_0, z_0)$ can be written as

$$\mathbf{P}(z_0, z_0) = \mathbf{D}(z_0)\mathbf{X}(z_0, z_0)\mathbf{S}^+(z_0), \tag{1}$$

where matrix $\mathbf{X}$ is the earth's transfer operator that includes the interaction with the surface (see Figure 1). In source matrix $\mathbf{S}^+$, each column represents a (directional) source, generating a downgoing source wavefield. In detector matrix $\mathbf{D}$, each row represents a receiver array, generating one seismic trace. The response of each source column is given by the corresponding column of data matrix $\mathbf{P}$.

Similarly, the result of one blended experiment is given by (Berkhout, 2008)

$$\mathbf{P}(z_0, z_0)\vec{\Gamma}_j(z_0) = \mathbf{D}(z_0)\mathbf{X}(z_0, z_0)\mathbf{S}^+(z_0)\vec{\Gamma}_j(z_0). \tag{2a}$$

Column vector $\vec{\Gamma}_j(z_0)$ represents the blending operator that contains the blending information (Figure 2a): elements $\Gamma_{kj}(z_0)$ are complex-valued scalars, describing time delays or a more complex code, whereas the involved sources are indicated by the positions $k$ of the scalars in column vector $\vec{\Gamma}_j(z_0)$. In our terminology, an N-fold blended source array contains N source units. The larger N, the more incoherent source energy is transmitted into the subsurface, implying also a larger signal to ambient noise ratio. Note that in the extreme case, a seismic survey consists of one mega-size blended shot record, indicating that a blended source array may have any size and the time shifts between the first and last shot may become very large. In such an extreme case, equation 2a represents the complete seismic survey (subscript $j$ can be deleted in equation 2a). Note that equation 2a is based on the linearity of seismic data in wavefields. This can be easily seen if we rewrite this equation as follows:

$$\sum_k \vec{P}_k(z_0, z_0)\Gamma_{kj}(z_0) = \mathbf{D}(z_0)\mathbf{X}(z_0, z_0)\sum_k \vec{S}_k^+(z_0)\Gamma_{kj}(z_0), \tag{2b}$$

showing that the weighted sources of the blended source array generate a weighted set of shot records, the latter being referred to as a blended shot record (see Figure 2b). Hence, an N-fold *blended* shot record is generated by an N-fold *blended* source array. Equation 2b can be made specific for marine data by showing explicitly the ghost effect. If we allow the individual elements $k$ of a blended source array to be at different depth levels $z_k$, then we may write

$$\sum_k \vec{P}_k(z_0, z_k)\Gamma_{kj}(z_k) = \mathbf{D}(z_0)\mathbf{X}(z_0, z_0)\sum_k \vec{S}_k^+(z_0, z_k)\Gamma_{kj}(z_k), \tag{3a}$$

where, assuming a surface reflectivity of $-1$,

$$\vec{S}_k^+(z_0, z_k) = \mathbf{W}^*(z_0, z_k)\vec{S}_k^+(z_k) - \mathbf{W}(z_0, z_k)\vec{S}_k^-(z_k). \tag{3b}$$

In equation 3b, matrix $\mathbf{W}(z_0, z_k)$ equals the propagation operator, describing the propagation between source depth $z_k$ and surface level $z_0$ and superscript $*$ denotes that the complex conjugate must be taken. Note that equations 2 and 3 assume that the earth is time-invariant and linear during seismic acquisition.

Let us consider the illumination properties of a blended source array. The incident wavefield at depth level $z_m$, being generated by blended source array $j$ at the surface $z_0$, is given by

$$\vec{\mathrm{P}}_j^+(z_m, z_0) = \mathbf{W}(z_m, z_0)\mathbf{S}^+(z_0)\vec{\Gamma}_j(z_0), \tag{4a}$$

or, looking at incident wavefield at gridpoint $i$ of depth level $z_m$,

$$\mathrm{P}_{ij}^+(z_m, z_0) = \vec{W}_i^\dagger(z_m, z_0)\mathbf{S}^+(z_0)\vec{\Gamma}_j(z_0). \tag{4b}$$

In equation 4b, superscript $\dagger$ denotes a row vector and $\vec{W}_i^\dagger$, being the $i$th row of propagation matrix $\mathbf{W}$. Row vector $\vec{W}_i^\dagger$ describes wavefield propagation from all source array points at surface level $z_0$ to subsurface gridpoint $i$ at depth level $z_m$ (many-to-one projection).

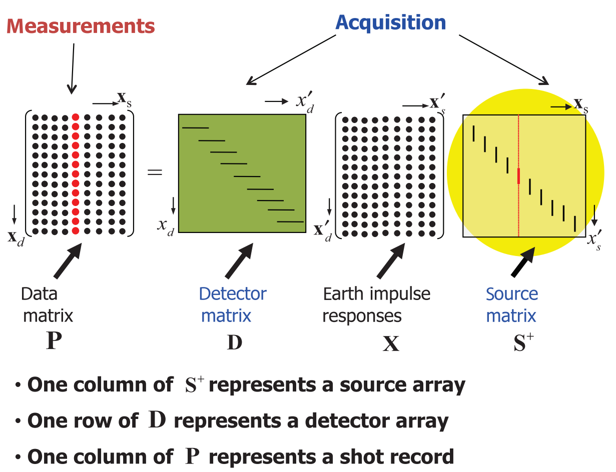


Figure 1. The data matrix represents a frequency slice of the total seismic data volume, the complex-valued scalar of each matrix element representing one Fourier component of a seismic trace. The model of the data matrix ($\mathbf{P}$) consists of the source matrix ($\mathbf{S}^+$), the earth's transfer matrix $\mathbf{X}$ and the detector matrix $\mathbf{D}$.

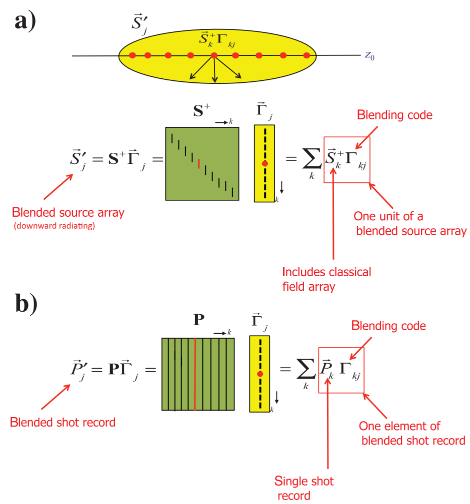


Figure 2. (a) One blended source array consists of a multitude of source units, each unit having its own code; (b) a blended shot record can be written as a linear combination of single shot records that are generated by the individual source units of the blended source array.

Note that the imaging step in migration should take the complex spectral properties of the incident wavefield $P^{+}_{ij}$ into account, implying that crosscorrelation, as we still see today, is not an acceptable imaging condition for the migration of blended wavefields.

## INHOMOGENEOUS BLENDING

For the design of blended source arrays, incident wavefield $P^{+}_{ij}$ must be judged by its temporal and spatial spectral properties at subsurface gridpoint $i$. From equation 4b, it follows that the individual sources at surface locations $k(\vec{S}^{+}_{k}\Gamma_{kj})$ need to be optimized by considering the properties of the composite incident wavefield at subsurface locations $i(P^{+}_{ij})$. It means that the individual sources of a blended array may consist of narrowband sources with different central frequencies (components), as long as the *sum* of all arriving components (composition result) satisfies the full bandwidth requirements. I refer to this concept as inhomogeneous blending. Figure 3 illustrates the principle by showing a blended shot record with five equal broadband source units (Figure 3a) and five different narrowband source units (Figure 3b).

According to the Nyquist sampling criterion, the ideal source spacing should be smaller than half the smallest wavelength that a source transmits. In case of different source types, e.g., low-, mid-, and high-frequency sources, it means that each type has its own optimum spacing, which is largest for the low-frequency sources and smallest for the high-frequency sources. Hence, the required number of low-frequency source positions is lower than the number of high-frequency source positions. I call this type of blended source configuration: dispersed source array (DSA).

It is important to realize that a DSA acts like a modern audio surround-sound system: the different speaker units are decentralized, taking care of the different subbands within the total audio frequency range. This subdivision leads to entirely different speaker designs for the low, mid, and high frequencies. The audio-seismic comparison highlights the fundamental difference of the DSA concept with acquisition systems, such as polychromatic acquisition (CREWS consortium) and SeisMovie (Meunier et al., 2001), where broadband source units operate in a multimonochromatic manner.

Inhomogeneous blending with DSAs has several attractive potential advantages: (1) The dedicated narrowband units of a blended array represent technically simple source units; (2) the signal emission properties of each source unit can be optimized for its central frequency (no engineering compromise); (3) destructive interference within a source array is avoided, allowing angle-independent source wavelets; (4) each source element has its own spatial sampling interval, allowing multiscale acquisition grids; (5) each source element has its own depth level, allowing ghost matching in the field (marine); (6) frequency shaping becomes an option during acquisition, and deblending will be a simple preprocessing step; (7) DSAs are more flexible to comply with the emerging strict regulation on sea life protection (marine).

All these potential advantages need be further developed and realized in the field. For instance, the advantage of different source designs and sampling intervals for the low, mid, and high frequencies may revolutionize the way land data is acquired and preprocessed. And in marine, the advantage of different source depths $z_k$ may be very large by choosing the central frequency $f_c$ of each source element in the maximum of the ghost transfer function (ghost matching): $f_c z_k = 0.25\ c_w$, with $c_w$ is the water velocity. It is interesting to mention here that the advantages of multilevel depth sources were already demonstrated in a EAGE workshop on marine seismic (Cambois and Osnes, 2009). Recently, the variable depth option was also proposed at the detector side, showing excellent results (Soubaras, 2010). Combining the two is the way to go.

## DSA EXAMPLES

To illustrate the DSA principle, a homogeneous medium is considered. Three source types are used: low-, mid-, and high-frequency sources with bandwidths 5–15, 10–30, and (25–75 Hz), respectively. One could think of three land vibrators with different central frequencies. Each of these vibrators has a relatively small seismic bandwidth, making them technically simpler and seismically more effective with respect to broadband alternatives. Because the sampling requirements depend on the emitted frequencies, we have chosen the number of low-, mid-, and high-frequency source units according to multiples of 1, 2, and 5, respectively. Note that these numbers are related to the central frequency of each of the source units. This means that, ideally, there are five times more high-frequency source positions than low-frequency source positions. In this 2D illustration, 96 source units were blended along a line of 6 km length: 12 low-, 24 mid-, and 60 high-frequency sources. The blending codes were simple: time delays only.

The incident wavefield $\vec{P}^{+}_{j}$ due to this blended source configuration was computed for all gridpoints at the depth level of 1000 m (Figure 4). Note the incoherent character of this incident wavefield. The different source types can be easily recognized. Although none

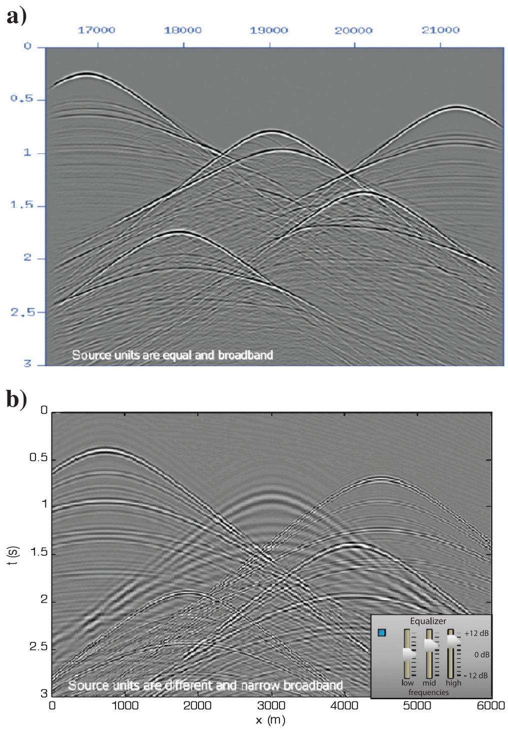


Figure 3. (a) A blended shot record that is generated by five equal broadband source units and five different narrowband source units, representing homogeneous and inhomogeneous blending, respectively. Note that with inhomogeneous blending frequency shaping becomes an option in the field for the compensation of absorption.

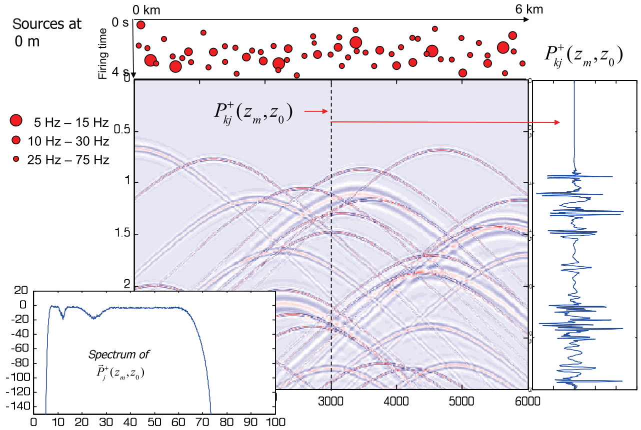


Figure 4. Incident wavefield at $z_m = 1000$ m, generated by a DSA at $z_0$ with three narrowband source units at 10, 20, and 50 Hz, together with its amplitude spectrum, the Fourier transformation being applied to the laterally averaged autocorrelation function. Note that the incident wavefield at gridpoint $i$, $\mathrm{p}_{ij}^{+}(z_m, z_0)$, represents a dispersed time series.

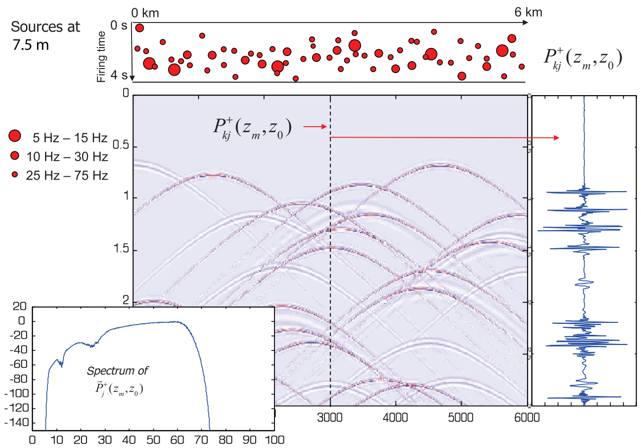


Figure 5. The same experiment as in Figure 4, but now for the marine situation, using a fixed depth level of 7.5 m for all source units.

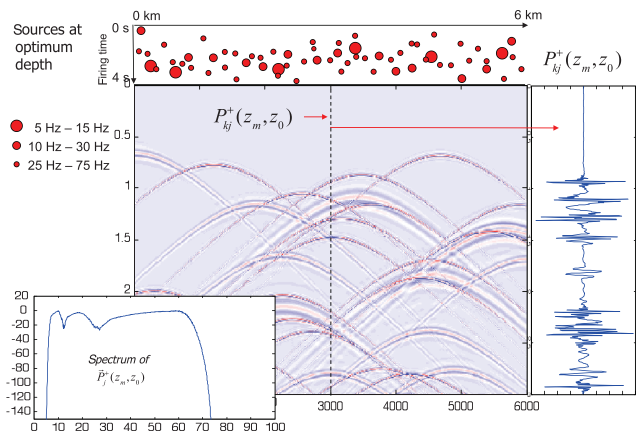


Figure 6. The same experiment as in Figure 5, but now for a variable depth level for each source unit, choosing $z_k = 0.25 c_w / f_c$ (ghost matching).

of the sources produces the required full temporal bandwidth, the spectrum of the total incident wavefield at depth level $z_m$, $\vec{\mathrm{P}}_j^{+}(z_m, z_0)$, does contain the full temporal spectrum. The signal illuminating the middle gridpoint $\mathrm{P}_{ij}^{+}(z_m, z_0)$ is also visualized in Figure 4. As expected, it represents a dispersed time series, showing the contribution of all units of the blended source array that are arriving at this gridpoint.

The experiment is repeated for the marine situation, using a fixed depth level of 7.5 m for all source units (see Figure 5) and a variable depth level by choosing $\mathrm{z_k} = 0.25\,\mathrm{c_w}/\mathrm{f_c}$ for each source unit (see Figure 6). Note the significant improvement at the low frequencies by applying ghost matching. Note also that a further improvement of the temporal spectrum can be realized by making the individual sources less narrowband or, alternatively, by extending the number of narrowbands (from three to four).

## CONCLUSIONS

In traditional seismic acquisition each individual source unit (such as a broadband seismic vibrator or a broadband air-gun array) has to transmit the full temporal bandwidth from a prespecified location. This makes the current seismic sources complex technical devices from a system engineering as well as wave transmission point of view. Compromises need be taken on the source design, on the source sampling interval and on the source depth level (marine).

Blended seismic acquisition aims at utilizing many more source units at many more locations for the same survey time. I propose to choose narrowband versions for these units, with the condition that the total incident wavefield in the subsurface exhibits the required spectral properties. As a consequence, these narrowband sources can be the result of no-compromise designs. In addition, they will be technically less complex and seismically more effective (less evanescent signal energy in the source area).

With a multitude of dedicated narrowband source units, being referred to as DSA, the blended incident wavefield at a particular subsurface gridpoint will contain the full temporal bandwidth. The incident wavefield at a subsurface gridpoint is represented by a dispersed time series, corresponding to a complex code, even if a simple source code like time delays is used. This time series contains broadband, multiangle, multiazimuth information. To avoid aliasing in the downgoing source wavefield, the theoretical spatial sampling requirements can be fulfilled by allowing high-frequency source units to be distributed more densely than low-frequency source units (multiscale shooting grids). In addition, in the marine situation source depths can be optimized (ghost matching).

The ever-increasing number of seismic sources has a practical limitation from the logistics point of view. The use of simple autonomous source boats with single air guns of different sizes (in marine) and simple autonomous source trucks with single vibrators of different sizes (on land) becomes a practical proposition in DSA acquisition. Similar to what we see already happening at the detector side, it may be the start of a far-reaching robotization process in seismic source operations as well.

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