Decentralized Blended Acquisition

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SUMMARY

The concept of blending and deblending is reviewed, making use of traditional and dispersed source arrays. The network concept of distributed blended acquisition is introduced. A million-trace robot system is proposed, illustrating that decentralization may bring about a revolution in the way we acquire seismic data in the future.

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 from a larger number of angles and, therefore, will improve the image quality in terms of signal-to-noise ratio and spatial resolution.

In the seismic literature, already an abundance of references on simultaneous shooting can be found. Examples of recent publications are Beasley (2008), Berkhout (2008), Howe et al. (2008), Pechols et al. (2010), Berkhout et al. (2012), Beasley et al. (2012), Abma et al. (2012), Krupovnickas et al. (2012).

In blended acquisition, being a special version of simultaneous shooting, the 'simultaneous' source wavefield is incoherent (see Figure 1).

Figure 1: Subdivision of simultaneous shooting methods, based on the degree of incoherency.

Such an incoherent wavefield is physically generated by firing a multitude of sources, each source with its own code (such as temporal delay, nonlinear phase function, pseudo-random time 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. The

objective of blended acquisition is to maximize the emission of full-bandwidth, non-aliased, far-field signal energy within a pre-specified 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. Today's seismic vibrators and airgun arrays are designed such that they have a large bandwidth, ranging over many octaves. In practice, however, such source designs are a compromise from a systems engineering point of view.

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 wide-band 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. In addition, I propose that the traditional *centralized* concept in seismic acquisition is replaced by a *decentralized* network alternative.

THEORETICAL CONSIDERATIONS

Seismic data can be arranged in data matrix $\mathbf{P}$. In the frequency domain $\mathbf{P}$ represents a frequency slice of the total data volume and one element P_{ij} is one frequency component of the trace measured 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 $\mathbf{P}$ can be written as (Berkhout, 1982):

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

where matrix $\mathbf{X}$ is the Earth's transfer operator that includes the interaction with the surface. In source matrix $\mathbf{S}^+(z_0)$ each column represents a (directional) source. In detector matrix $\mathbf{D}$ each row represents a receiver (array). The response of each source column ($\vec{S}_j^+$) is given by the corresponding column of the data matrix ($\vec{P}_j$).

Using expression 1, the result of one blended experiment can be formulated by (Berkhout, 2008):

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

Column vector $\vec{\Gamma}_j(z_0)$ contains the blending information. This is illustrated in Figure 2: elements $\Gamma_{kj}(z_0)$ are complex-valued scalars, describing time delays or a more complex code, while the involved sources are indicated by the positions (k) of the scalars in column vector $\vec{\Gamma}_j(z_0)$. Note that equation 2a is based on the linearity of seismic data in wavefields. This can be eas-

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Figure 2: One blended source array consists of a multitude of source units, each unit having its own code.

ily seen if we rewrite this equation as follows:

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

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. 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:

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

where, assuming a surface reflectivity of -1,

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

In equation 3b matrix $\mathbf{W}(z_0, z_k)$ describes the propagation between source depth z_k and surface level z_0 and superscript * denotes the complex conjugate. Note that the incident wavefield in gridpoint i at depth level z_m , being generated by blended source array j at the surface z_0 , is given by:

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

Here, $\vec{W}_i^\dagger$ describes wavefield propagation from all source array points at surface level z_0 to subsurface gridpoint i at depth level z_m .

From the foregoing it follows that blended acquisition has two important advantages: (1) the number of source points per km^2 is increased and (2) the survey time per km^2 may be decreased. Both aspects refer to data quality: more signal energy per unit area and unit time is transmitted into the subsurface (less spatial aliasing and larger signal to background noise ratio). The second aspect also refers to economics. Particularly in special situations, think of areas where access is restricted to a limited period of time, blending may be the only solution that is practically feasible.

DESCRIPTION OF DEBLENDING ALGORITHM

In deblending, blended measurements are given and unblended data need be computed (inversion process). In this closed-loop process, numerically simulated measurements - output of forward modeling according to equations 2a and 2b - are compared with the real measurements. By minimizing the difference between the two datasets the unblended samples (parameters) can be estimated. To explain this inversion process, let us minimize the following unconstrained least-squares criterion (z_d and z_s are omitted for notational convenience):

$$\|\Delta \vec{P}_j'\|^2 = \|\vec{P}_j' - \mathbf{P} \vec{\Gamma}_j'\|^2. \quad (5a)$$

Bear in mind that in minimization equation 5a

$$\mathbf{P} \vec{\Gamma}_j' = \sum_k \vec{P}_k \Gamma_{kj} \quad (5b)$$

represents the modeling output and vector $\vec{P}_k$ equals the deblended shot record for shot k . The iterative solution of minimization problem 5a is given by:

$$\vec{P}_k^{(i)} = \vec{P}_k^{(i-1)} + [\Delta \mathbf{P}']^{i-1} \Lambda \vec{\Gamma}_k^H, \quad (6)$$

where diagonal matrix Λ contains the weights.

The validity of iterative, weighted, least-squares solution 6 can be quickly verified by substituting the expression of $\Delta \mathbf{P}'$ in equation 6, leading to the well-known analytic equation:

$$\mathbf{P}' \Lambda \vec{\Gamma}_k^H = \mathbf{P} [\Gamma \Lambda \vec{\Gamma}_k^H], \quad (7)$$

where $\vec{P}_k^{(i)}$ in 6 is approaching $\vec{P}_k$ in 7 asymptotically.

In the first iteration ($i = 1$) $\Delta \mathbf{P}' = \mathbf{P}'$, meaning that the inversion process starts with pseudo-deblending. It is interesting to realize that Λ may be a scaled unity matrix or a diagonal matrix or a bandmatrix, depending on the properties of blending matrix Γ . During the presentation properties of the algorithm will be illustrated with examples. The computational diagram is shown in Figure 3.

Figure 3: Computational diagram of deblending in terms of inversion, showing the four principal algorithmic modules (estimation, selection, modeling and subtraction) in each iteration.

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DISPERSED SOURCE ARRAYS

For the design of blended source arrays, the individual sources at surface locations k ($\vec{S}_k^+ \Gamma_{kj}$), see equation 4, 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 ('composite result') satisfies the full bandwidth requirements.

According to the Nyquist criterion, the ideal source spacing should be smaller than half the smallest wavelength 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. Note that this is largest for the low-frequency sources and smallest for the high-frequency sources! 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 system: the different loudspeaker units are decentralized, taking care of the different sub-bands within the total audio frequency range. This subdivision leads to entirely different loudspeaker designs for the low, mid and high frequencies (see Figure 4). The audio-seismic comparison highlights the fundamental difference of the DSA concept with systems such as Polychromatic Acquisition (CREWES consortium) and SeisMovie (Meunier et al., 2001), where broadband source units operate in a multi-monochromatic manner.

Figure 4: Application of the DSA concept in broadband high performance audio systems. Note the significantly different designs for the different frequency bands.

Inhomogeneous blending with DSAs has a number of attractive potential advantages: (1) the dedicated narrowband units of a blended array represent technically simple, no-compromise source units, (2) destructive interference within a source array is avoided, allowing angle-independent source wavelets, (3) each source type has its own spatial sampling interval, allowing multi-scale acquisition grids, (4) each source type has its own depth level, allowing ghost matching in the field (marine), (5) deblending DSA data is relatively simple: the first step (source decoding + bandpass filtering) is already very effective, (6) DSAs are more flexible to comply with the emerging strict regulation on sea life protection (marine).

It is interesting to mention here that the advantages of multi-level depth sources were already demonstrated in a EAGE workshop on marine seismic in Cyprus (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.

DECENTRALIZED BLENDED ACQUISITION

Based on the blending method and the DSA concept, it is proposed to make another fundamental improvement in seismic data acquisition. This improvement is achieved by changing the system architecture. I propose to focus future acquisition developments on the major opportunities that are offered by the decentralized network architecture. By moving from a *single* complex, centralized system to a *network* of simple, decentralized subsystems, more information is collected with less complexity.

Decentralization is the major change we have seen in many technological solutions during the last decade; particularly think of information, communication and computation systems in the IC-sector. Central systems have been transformed to networks, increasing the capability and efficiency beyond expectation. Figure 5 visualizes two system architectures. Figure

Figure 5: Two types of system architectures. Until today, seismic acquisition occurs with a centralized architecture (a).

5a shows schematically a conventional broadcast architecture, allowing N one-way connections from the central source subsystem to the N receiver subsystems. Hence, with this architecture the information received increases linear with N . Figure 5b shows a decentralized network architecture, where every element functions both as a source and receiver subsystem. Now there exist N^2 connections in the network, meaning that the information received increases quadratically with N , see Figure 6.

Figure 6: The difference in information content between a centralized and decentralized system.

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If we look at the current seismic acquisition systems, then we may conclude that the industry makes use of the so-called broadcast architecture: one seismic source (array) sends its energy - via the Earth - to the N seismic detectors. In the past decades we have seen that the number of detectors have been continuously increased to as much as 100.000 and further increases are in progress. This has increased the complexity of the acquisition system tremendously. Actually, current seismic systems are great technological achievements.

I propose to the industry to abandon the centralized acquisition concept: the linear relationship is not an attractive proposition. Instead, it is proposed to concentrate on the exciting opportunities that are offered by the network architecture. For example, if we use an acquisition network with a swarm of 100 simple source-detector subsystems, where each subsystem consists of a DSA robot dragging one short 100-detector cable, then the total number of traces per blended shot record equals one million traces (100×100^2)! Figure 7 gives an artist impression of such a network.

Figure 7: Artist impression of a distributed seismic acquisition network. Each robot consists of an optimized narrowband source and a small detector array, e.g., with 100 receivers only. A swarm of one hundred of these robots configure a one million trace system.

CONCLUSIONS

With a multitude of dedicated narrow-band source units, being referred to as Dispersed Source Arrays, the blended incident wavefield at a particular subsurface gridpoint contains broadband, multi-angle, multi-azimuth information. The theoretical spatial sampling requirements can be fulfilled by allowing low-frequency sources to be distributed more sparsely than high-frequency sources ('multi-scale shooting grids'). In the marine case source depths can be optimized ('ghost matching').

It is also proposed to rethink the centralized acquisition concept. Instead, I propose to concentrate future developments on the network architecture concept, where information collection is linear in the number of detectors (N). A plea is made to

concentrate future developments on the network architecture concept, showing a quadratic behavior in seismic information (N^2).

By moving from a single complex, centralized system to a network of simple, decentralized subsystems, robotization becomes an attractive proposition: a one million channel system can be realized by a small number of simple source-detector robots.

FINAL REMARK

Berkhout and Blacquiere (2012) conclude that the signal to background-noise ratio of a field-blended survey must be higher than of a comparable traditional survey. This is because the power of the signal (total signal energy divided by the effective survey time) increases in blended acquisition, not only because the number of sources increases, but also due to the fact that the survey time may decrease. On the other hand, the power of the background noise is independent of whatever we do in the blending process. Hence, a shorter recording time not only favors economics, it also favors *quality*, particularly in areas with a high background noise level. This conclusion emphasizes the enormous potential of blended acquisition for the industry. As a consequence, I expect that unblended seismic acquisition will become a technology of the past.

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EDITED REFERENCES

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REFERENCES

- Abma, R., Zhang, Q., Arogunmati, A., and Beaudoin, G., 2012, An overview of BP's marine independent simultaneous source field trials: 82nd Annual International Meeting, SEG, Expanded Abstracts, <http://dx.doi.org/10.1190/segam2012-1404.1>.
- Beasley, C. J., B. Dragoset, and A. Salama, 2012, A 3D simultaneous source field test processed using alternating projections: A new active separation method: *Geophysical Prospecting*, **60**, 591–601, <http://dx.doi.org/10.1111/j.1365-2478.2011.01038.x>.
- Beasley, C. J., 2008, A new look at marine simultaneous sources: *The Leading Edge*, **27**, 914–917, <http://dx.doi.org/10.1190/1.2954033>.
- Berkhout, J., and G. Blacquière, 2012, Utilizing dispersed source arrays in blended acquisition: 82nd Annual International Meeting, SEG, Expanded Abstracts, <http://dx.doi.org/10.1190/segam2012-0302.1>.
- Berkhout, A., D. Verschuur, and G. Blacquière, 2012, Illumination properties and imaging promises of blended, multiple-scattering seismic data: A tutorial: *Geophysical Prospecting*, **60**, 713–732, <http://dx.doi.org/10.1111/j.1365-2478.2012.01081.x>.
- Berkhout, A. J., 1982, *Seismic migration, imaging of acoustic energy by wave field extrapolation. Part A: Theoretical aspects*: Elsevier.
- Berkhout, A. J., 2008, Changing the mindset in seismic data acquisition: *The Leading Edge*, **27**, 924–938, <http://dx.doi.org/10.1190/1.2954035>.
- Doulgeris, P., K. Bube, G. Hampson, and G. Blacquière, 2012, Convergence analysis of a coherency-constrained inversion for the separation of blended data: *Geophysical Prospecting*, **60**, 769–781, <http://dx.doi.org/10.1111/j.1365-2478.2012.01088.x>.
- 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, <http://dx.doi.org/10.1190/1.3063932>.
- Krupovnickas, T., K. Matson, C. Corcoran, and R. Pascual, 2012, Marine simultaneous source OBS survey suitability for 4D analysis: 82nd Annual International Meeting, SEG, Expanded Abstracts, <http://dx.doi.org/10.1190/segam2012-0815.1>.
- Meunier, J., F. Huguet, and P. Meynier, 2001, Reservoir monitoring using permanent sources and vertical receiver antennae: The Céré-la-Ronde case study: *The Leading Edge*, **20**, 622–629, <http://dx.doi.org/10.1190/1.1439008>.
- Pecholcs, P. I., S. K. Lafon, T. Al-Ghamdi, H. Al-Shammery, P. G. Kelamis, S. X. Huo, O. Winter, J.-B. Kerboul, and T. Klein, 2010, Over 40,000 vibrator points per day with real-time quality control: Opportunities and challenges: 80th Annual International Meeting, SEG, Expanded Abstracts, 111–115, <http://dx.doi.org/10.1190/1.3513041>.