Simultaneous sources: recent advances in marine acquisition and processing

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SUMMARY

Until recently, seismic data acquisition has been fundamentally limited by the requirement that the delay time between one shot and the next be sufficient to avoid significant contamination of data from one shot with energy from another. Acquisition with simultaneous sources drops this requirement, and therefore provides potential for enormous improvements in acquisition rates and source sampling. In order to realize this potential however, the way we acquire and process data must change.

Although simultaneous-source technology is already a commercial reality for both land and marine acquisition, there is considerable scope for further optimization, especially in the marine case. In this work, I address the specific issue of relaxing the constraint that sources fire near-synchronously, such that the options for survey design in particular are greatly increased. I show that separation into individual shot records is possible even with arbitrary shot firing times, provided those times have some randomness to them. I address the major issue of removing strong interference from deep data, and show how this can be significantly improved by supplying prior information about the expected general decay of amplitude with time. Simulated simultaneous-source data, for which the correct answer is known, are used to illustrate the method.

Key words: blending, separation, sampling, efficiency.

INTRODUCTION

In general, simultaneous-source acquisition reduces the delay time between shots to the point where there is significant interference between them. This reduction in the shot time interval (STI) can enable enormous improvements in acquisition efficiency, especially when multiple sources are available.

Interference to a given shot comes from both earlier and later shots. In general, the interference from earlier shots is relatively weak because the longer travel time corresponds to greater geometric spreading and attenuation. Interference from later shots is, however, strong, especially if the corresponding STI is large. Figure 1 shows examples of simultaneous-source shots for small and large STIs.

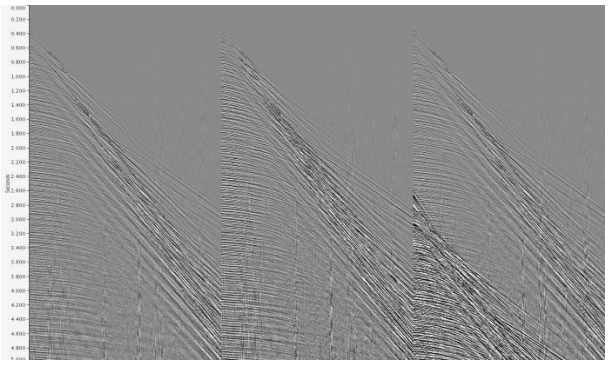

Figure 1. Sequential (left) and simultaneous-source shot gathers with small (middle) and large (right) STIs. When the STI is small, the amplitude levels from the two shots are comparable at all times. When the STI is large, however, there is a significant strong-on-weak effect for the deep data, especially for the near offsets.

I define synchronous shooting to be the case in which the survey is designed such that the STIs for interfering shots are always small. Typically, this is the case when multiple sources shoot near-simultaneously, and the next set of shots is not taken until the desired record length has been acquired. This was the case presented by Moore *et al.* (2012), for example.

Synchronous shooting requires that there are periods, equal to the desired record length, during which no shots are taken. For marine acquisition with continuously-moving sources, this requirement translates into a minimum shot point interval (SPI) for each source. Acquiring data with a smaller SPI than this requires that the shots are asynchronous, i.e. that shots can be taken with STIs that are a significant portion of the record length. Whilst asynchronous shooting is quite normal for land data, it has seen very little application for marine data because the strong-on-weak interference (Figure 1) that is generated is very difficult to remove. Separation is also complicated because the shots cannot be grouped into interfering sets, but rather the recorded data need to be considered as a continuous stream.

As well as allowing for a reduced SPI, asynchronous shooting allows for "self-interference", i.e. for interference between shots from the same source. Simultaneous-source marine acquisition is therefore not limited to situations in which multiple sources are available.

Recorded data contain both shot-generated energy ("signal") and ambient noise. Ambient noise is, by definition, not associated with a known source, and is therefore not separable.

Care must be taken that the presence of ambient noise is not significantly detrimental to the separation process.

The following sections describe the methodology used to separate data acquired with asynchronous shooting, and exemplify it using a simulated simultaneous-source dataset.

METHOD AND RESULTS

Rather than assuming that the recorded dataset consists of many "blended shots" each of which is the sum of a small number of individual shots, as many authors have done in the past (Moore *et al.*, 2008; Berkhout, *et al.*, 2012), I consider the recorded data for each channel to be a single, continuous data stream, $d(T)$. The upper-case T is used to distinguish "acquisition time" from the usual "time-since-shot" (two-way time), t. The data stream contains signal due to an arbitrary number of shots taken at arbitrary times and locations, together with ambient noise. Mathematically,

$$d(T) = \sum_i w_i(t) * g(\mathbf{s}_i, \mathbf{r}(T), T - T_i) + n(T)$$

where $g(\mathbf{s}, \mathbf{r}, t)$ is the impulse response (Green's function) at time t and receiver location $\mathbf{r}$ due to an impulsive source taken at time zero and location $\mathbf{s}$. The location, time and wavelet for the ith shot are denoted $\mathbf{s}_i$, T_i and w_i, respectively, $n(T)$ represents the ambient noise, and $*$ denotes convolution.

Passive separation (pseudo-deblending) simply involves extracting the portion of the continuous data stream associated with each shot, i.e.

$$d_i^p(t) = d(T_i + t)$$

for a range of t equal to the desired record length. This does nothing to remove the interference from other shots (or the ambient noise), but guarantees that any signal in the recorded data is preserved.

Active separation, however, attempts to remove the interference (and, potentially, the ambient noise) whilst preserving the signal. For marine data with continuously-moving sources, the location of source S is a known function, $\mathbf{s}(T, S)$, and the shot locations are given by $\mathbf{s}_i = \mathbf{s}\big(T_i, S(i)\big)$ where $S(i)$ is a function that maps the shot number to the corresponding source number. Similarly, the Green's function may be written

$$g(\mathbf{s}_i, \mathbf{r}(T), T - T_i) = \tilde{g}\left(\mathbf{s}\big(T_i, S(i)\big), t, S(i)\right)$$

where $t = T - T_i$ and I note that the receiver location is implied by the source location and t, because together these define T.

Active separation assumes that the Green's function for a given source is coherent as a function of shot location. Typically (see, for example, Moore *et al.*, 2008), this is done by assuming that the Green's function has a sparse representation in some transform domain which utilizes "seismic-like" basis functions. Examples of such a domain are the curvelet and Radon domains. In the latter case, we can write

$$\tilde{g}(\mathbf{s}, t, S) = R(m(\mathbf{p}, \tau, S), \mathbf{s}, t, S)$$

where R is a linear operator that maps data from the Radon domain to the shot-time domain, $m(\mathbf{p}, \tau, S)$ is the model, i.e. the representation of the data in the Radon domain, and τ and $\mathbf{p}$ are the usual Radon domain time and slowness parameters, respectively.

Defining $\mathbf{m}$ to be a vector formed by serializing the models for all sources, slownesses and times, and $\mathbf{d}$ and $\mathbf{n}$ to be the recorded data and ambient noise, respectively, written as vectors, then the above equations can be combined to yield

$$\mathbf{d} = BWR\mathbf{m} + \mathbf{n}$$

where R is the Radon operator (in matrix form) that generates data for the individual shots, W is a matrix operator that convolves these data with the appropriate source wavelets, and B is a blending operator that shifts the data to the appropriate acquisition times and sums them over shots. This is a linear system and can be inverted for $\mathbf{m}$ using sparse inversion techniques, after which the separated data can be estimated by omitting the blending operation, i.e. $\mathbf{d}^a = WR\mathbf{m}$. $\mathbf{d}^a$ can then be deserialized to yield $d_i^a(t)$, the actively-separated data.

The modelling process involves a residual of unseparated energy given by $\mathbf{r} = \mathbf{d} - BWR\mathbf{m}$. Theoretically, the residual contains the ambient noise and therefore separation can remove this noise. In practice, however, the residual will contain signal that is not sufficiently strong or coherent to be modelled. In order to avoid losing this signal, it is normal to add the residual (after passive separation) to the actively-separated data.

The linear system is generally highly underdetermined, especially when the blending factor, i.e. the average number of interfering shots, is high. For correct separation, it is important that energy is modelled at the correct place in the model domain. Requiring the model to be sparse helps achieve this objective, but there is still potential for leakage, i.e. for energy to be allocated to the wrong shot, when the interference appears coherent due to random chance or poor survey design. Additional constraints on the model (prior information) other than sparseness can be used to mitigate this effect. For example, if there is some prior knowledge of the dip content of the data, then this dip structure can be imposed on the model. A constraint that is particularly effective for asynchronous data with large STIs is to enforce a general amplitude decay with time on the model, such that very strong energy cannot easily be associated with late times. This means that strong interference from a later shot tends to be properly recognised as interference, rather than being interpreted as an unrealistically-strong, deep event.

Example

A powerful method to test separation algorithms is by simulation. Simulation takes real data recorded sequentially (such that there is little interference between shots) and constructs a continuous data stream containing significant interference by allocating acquisition times to the shots with appropriate STIs, and summing them. The simulated dataset is realistic, because it is based on real data, and the correct answer, at least in terms of the shot-generated energy, is known. It should be noted, however, that the real data will contain some ambient noise for which there is no correct separation. The ambient noise content of the simulated data stream will, therefore, be higher than that in an acquired simultaneous-source data stream.

Figure 2 shows a common channel (near offset) from the sequential and simulated simultaneous-source data sets. The strong-on-weak effect and the apparent incoherence of the interference from the following shots are evident. The interference is so strong that the underlying reflectors are not visible.

Figure 3 shows the results of active separation for the simulated data shown in Figure 2. Active separation was performed both with and without prior information. The Radon domain parameterization was held constant and chosen appropriately for the slowness (dip) content of the data. The prior information describes the expected amplitude decay with time. It does not contain any small-scale details about individual reflectors, but simply captures the overall decay due to geometric spreading.

In both cases, almost all of the interference is removed and the underlying reflectors are revealed. The interference is so strong, however, that the residual interference is of comparable amplitude to the underlying signal at some locations. This residual interference represents signal loss, because that part of the signal has been allocated to the wrong shot. The use of prior information significantly reduces the level of residual interference.

Figure 4 shows the differences between the actively-separated data in Figure 3, and the sequential data in Figure 2. The source-related content of these differences represents the separation error. The error is significantly reduced by the use of prior information.

CONCLUSIONS

I have described a methodology for the separation of simultaneous-source data considered to be a continuous recording such that the shot timing is completely generalized. Examples on simulated data demonstrate that the interference can be removed effectively, even when it is very strong. The use of simple forms of prior information, such as the expected amplitude decay due to geometric spreading, is shown to improve the results.

The examples shown here are for a near-offset, which is the most difficult to separate because the interference extends over a long time and is at its strongest. At sufficiently-large offsets, there may be no interference at all, as indicated in Figure 1.

The example dataset shown here contains some ambient noise, as shown in Figure 1. Although space precludes a detailed analysis, the separation method is robust to ambient noise, and in fact simultaneous-source acquisition naturally contains less ambient noise relative to the signal compared to sequential data, because the source effort is greater.

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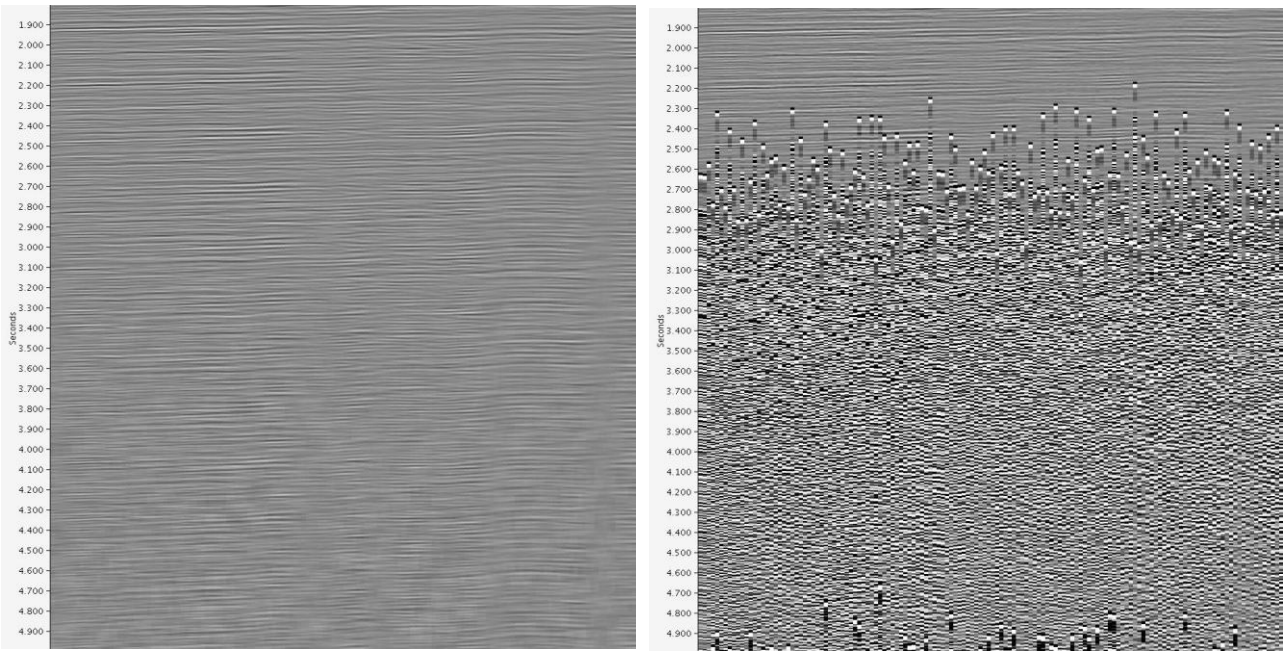

Figure 2. Sequential (left) and simulated simultaneous-source data (right, after passive separation). The interference from the following shot is very strong. Even stronger interference from the shot after that is visible at the bottom of the record.

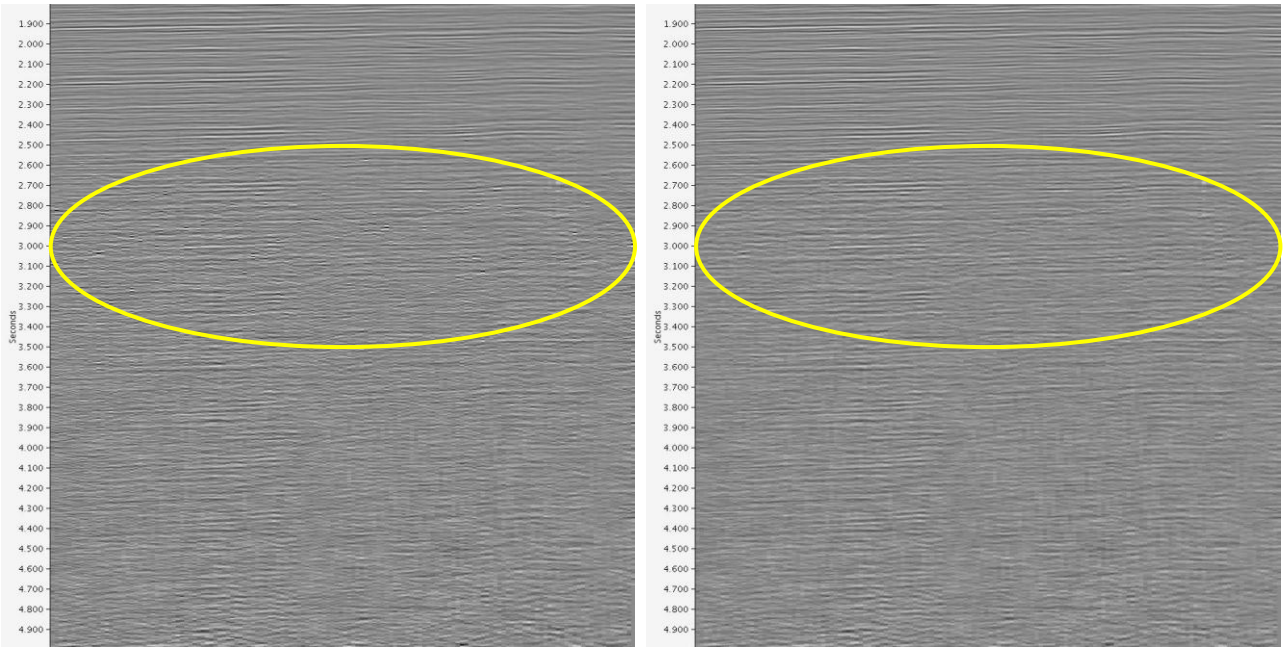

Figure 3. Active separation without (left) and with (right) prior information about the expected amplitude decay due to geometric spreading. In both cases, active separation removes most of the interference. Without priors (left) some interference from the following shot remains because it is modelled as strong, deep signal. The yellow ellipse indicates the zone where the residual interference is strongest. This interference is significantly reduced by the use of the prior, which discourages the inclusion of deep events that are unreasonably strong in the model.

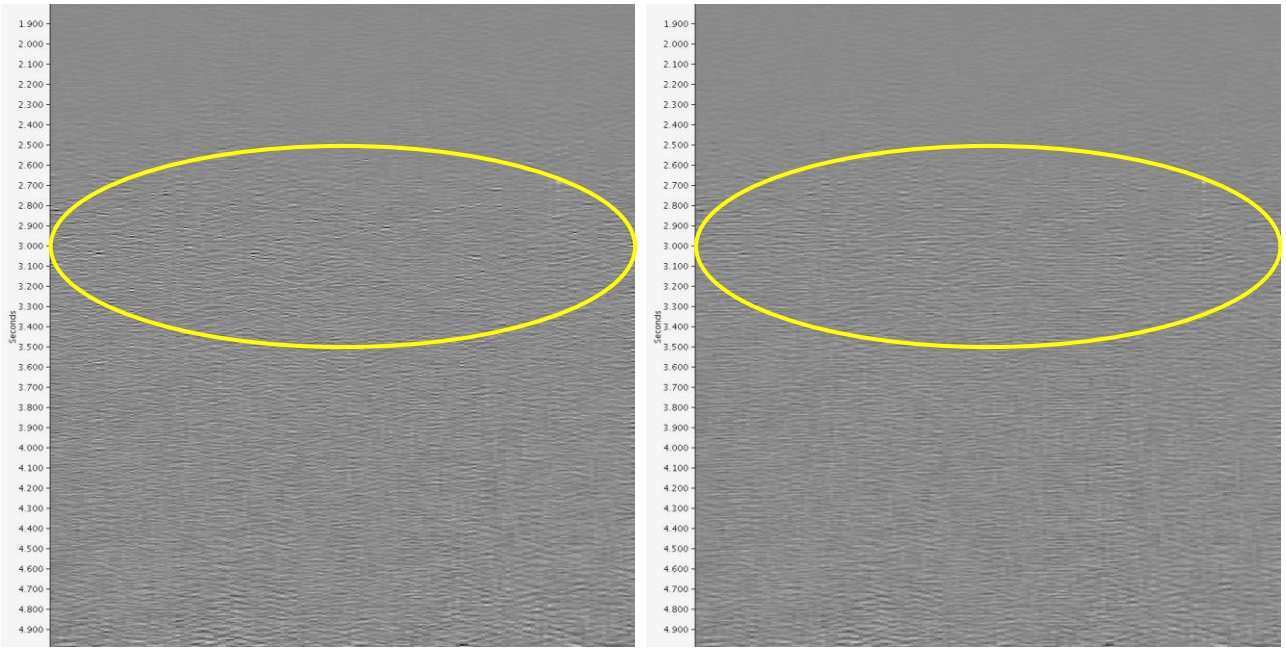

Figure 4. The differences between the separated data shown in Figure 3 and the sequential data shown in Figure 2. These differences represent the separation error, though they can also be expected to contain some ambient noise. The error when the prior is used (right) is significantly lower than that without the prior (left). The yellow ellipse is the same as that in Figure 3. Both differences contain only small amounts of signal, especially considering the extreme strength of the interference.