Effect of Noise in Blending and Deblending
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SUMMARY
We show that deblended shot records have a better background-related S/N than shot records in unblended surveys. This improvement increases with increasing blending fold and decreasing survey time. An interesting consequence of this property is that blended surveys can be carried out under more severe noise conditions than unblended surveys. It is advised to optimize the survey time in areas with a large background noise level or in areas with severe environmental restrictions or in areas where access is only for a limited time period. We conclude with the observation that unblended seismic acquisition may become a technology of the past.

INTRODUCTION
A seismic shot record contains the Earth response of planned, man-made sources as well as signals from other sources such as industrial activities, traffic, wind, and in the marine case also flow noise, breaking waves, etc. In addition, such a record contains noise that is related to the acquisition equipment, e.g., electronic noise, quantization noise, etc. The recorded events that are not related to the planned source(s) are referred to as the background noise. We will assume that the background noise is stationary, meaning that its power is time-invariant during the survey. One of the valuable properties of seismic blending is that in a blended survey more sources can be deployed within a certain survey time than in the corresponding unblended survey. This is because it is no longer needed to wait for all reflections to be recorded before firing the next source.

In the seismic literature (Beasley, 2008; Berkhout, 2008; Howe et al., 2008; Pechnoc et al., 2010; Berkhout et al., 2012; Abma et al., 2012; Krupovnickas et al., 2012), this property – keeping the survey time within limits – is considered to be a benefit related to economics. Beasley et al. (2012), however, suspect that the observed higher resolution in their field results is not only due to the improved source sampling characteristics of blended acquisition. They argue that the signal-to-noise ratio of blended data is likely to be higher than that of traditionally acquired data and they speculate that this property of blending may explain why their improvements are beyond expectation. 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.

In this paper our conclusion is explained by a theoretical analysis and the results are illustrated by numerical examples.

S/N RATIO IN BLENDED DATA
Let us consider the situation of the responses of $M$ sources that are either recorded individually, leading to $M$ unblended shot records, or that are recorded in a blended fashion, leading to $1$ blended shot record.

According to Berkhout (1982) individually acquired shot records can be formulated as:

$$\vec{P}_k = \mathbf{D} \mathbf{X} \vec{S}_k + \vec{N}_k$$

In equation 1 matrix $\mathbf{X}$ is the Earth’s transfer operator that includes the interaction with the surface. Source vector $\vec{S}_k$ represents source (array) $k$, generating a downgoing source wavefield. In detector matrix $\mathbf{D}$ each row represents a receiver (array), generating one seismic trace. The response of source $k$ is given by data vector $\vec{P}_k$. It includes background noise realization $\vec{N}_k$. We consider noise realizations in the different shot records to be uncorrelated. In the frequency domain, equation 1 refers to one frequency component.

When acquired in a blended way, i.e., field blending, the obtained blended shot record is given by (Berkhout, 2008):

$$\vec{P}^\prime = \mathbf{D} \mathbf{X} \vec{S}^\prime + \vec{N}$$

or,

$$\vec{P}^\prime = \mathbf{D} \mathbf{X} \sum_{k=1}^{M} \vec{S}_k \gamma_k + \vec{N}$$

where superscript $'$ indicates blending, $\vec{N}$ equals the background noise in blended field record $\vec{P}^\prime$ and where $\gamma_k$ represents the blending code (being some phase operator). For instance, if time delays $\tau_k$ are applied we may write $\gamma_k = \exp(-j\omega\tau_k)$. Note that the power of noise realization $\vec{N}$ in equations 2a,b equals the power of noise realization $\vec{N}_k$ in equation 1.

We start with the situation that the survey duration $T'$ of the blended survey is the same as the survey duration $T$ of the unblended survey. Note that survey duration should be interpreted here as ‘effective’, meaning that it corresponds to the total recording time. Note also that for the equal duration situation ($T' = T$), the blending performance indicator $BPI$ is given by (Berkhout, 2008):

$$BPI = (N'_s/N_s) \times (T/T') = N'_s/N_s = M$$

where $N'_s$ equals the number of sources in the blended survey and $N_s$ equals the number of sources in the unblended survey. We refer to the ratio $N'_s/N_s$ as the blending fold.

Apart from blending in the field (physical blending), we can also blend shot records in the computer (numerical blending):

$$\vec{P}^\prime = \mathbf{P} \vec{F}$$

where
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or, substituting equation 1,

\[ \vec{F}' = DX \sum_{k=1}^{M} \vec{S}_k \gamma_k + \sum_{k=1}^{M} \vec{N}_k \gamma_k, \quad \text{(4b)} \]

where the power of \( \vec{N}_k \gamma_k \) equals the power of \( \vec{N}_k \) (\( \gamma_k \) is a phase operator). If we now compare the data set that was blended in the field (equation 2b) with the one blended in the computer (equation 4b), it becomes clear that the latter contains more noise. In the case of numerical blending the noise is the sum of \( M \) noise realizations, whereas it is just a single noise realization in the case of field blending. Note that summing the uncorrelated noise means an increase of \( \sqrt{M} \) of the noise power. We illustrate the above theory by a simple numerical example, see Figure 1.

In Figure 2 numerical blending and physical blending are simulated for the case that \( M = 5 \) and results are compared. In the case of physical blending, one random noise realization was added to the noise-free blended shot record. In the case of numerical blending, a random noise realization was added to each individual unblended shot record first. All random noise realizations were given the same power and the blending processes in the computer and in the field were exactly the same. The difference in S/N can be observed by comparing Figure 2a and 2b. The noise levels were computed and, as expected, the results confirmed the theory (\( \sqrt{5} \)).

### S/N RATIO IN DEBLENDED DATA

Now, let us look in the deblended domain and compare the result of a deblending process on field-blended data with unblended field data, see the left route in Figure 3. Note that deblending is carried out by minimizing the following expression for all blended shot records (weighted least-squares minimization):

\[ (\vec{F}' - \sum_{k=1}^{M} \vec{P}_k \gamma_k)^H \Lambda (\vec{F}' - \sum_{k=1}^{M} \vec{P}_k \gamma_k) = \text{minimum}. \quad \text{(5)} \]

Here \( \vec{P}_k \) is a deblended shot record and \( \Lambda \) is a diagonal matrix. Note that in practice constraints are needed such as causality.

In addition, deblending algorithms often include some coherence filtering in the receiver domain (Doulgeris et al., 2012; Abma et al., 2012; Beasley et al., 2012). The deblending result can be presented by the following expression:

\[ < \vec{P}_k > = DX \vec{S}_k + \Delta \vec{N}_k + \delta \vec{N}_k \quad \text{for} \quad k = 1, \ldots, M, \quad \text{(6)} \]

where \( \Delta \vec{N}_k \) equals the background noise and \( \delta \vec{N}_k \) equals the residual blending noise. Bear in mind that after re-blending the deblended shot records, the difference with the blended field data is minimum according to equation 5. Typically, we find

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Figure 1: Blended data can be generated in the field (physical blending) or in the computer (numerical blending). Both data sets can be compared.

Figure 2: Comparison between numerical blending (a) and field blending (b), using a blended array with 5 sources. As expected, the signal-to-noise ratio of the field-blended data is a factor of \( \sqrt{5} \) better than of the numerical-blended data.

Figure 3: Unblended seismic data can be compared with deblended field-blended data (left) and with deblended numerical-blended data (right).
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Figure 4: Comparison between unblended field data (a) and the result of deblending field-blended data (b), using again a blended array with 5 sources. As expected, the signal-to-noise ratio of the deblended field data is a factor of $\sqrt{5}$ better than that of the unblended field data.

that the residue is in the order of -20 dB. This means that we may write within the accuracy of the residue levels:

$$\vec{N} = \sum_{k=1}^{M} \Delta \vec{N}_k \gamma_k.$$  \hspace{1cm} (7)

From equation 7 we may conclude that the background-related S/N in the deblended field data (equation 6) is $\sqrt{M}$ higher than in the unblended field data (equation 1). As suggested by Beasley et al. (2012) this property could be exploited in marine by extending the weather window in blended acquisition. On the other hand, it is interesting to realize that in the case of calm weather the source level could be reduced. This means that blending offers also an attractive opening to minimize the negative effects on sea life. Note that for numerically blended data - see the right hand side in Figure 3 - noise equation 7 needs to be modified to:

$$\sum_{k=1}^{M} \Delta \vec{N}_k \gamma_k = \sum_{k=1}^{M} \Delta \vec{N}_k \gamma_k$$ for $k = 1, \ldots, M,$ \hspace{1cm} (8)

showing that in numerically blended data the deblended data has the same background-related S/N as the unblended field data.

We illustrate again the theory by the same numerical example: the deblended field records have been compared with the corresponding unblended field results. The difference in S/N can be clearly observed in Figures 4a and 4b. The noise levels were computed, confirming that deblending increases the background S/N by the blending fold ($\sqrt{5}$). We also show the results for the numerically blended data (compare Figures 5a and 5b). As expected, the S/N in deblended and unblended data is the same. Figure 6 summarizes all results.

Figure 5: Comparison between unblended field data (a) and the result of deblending numerically blended data (b), using again a blended array with 5 sources. As expected, the signal-to-noise ratio is the same in the two cases.

Figure 6: The S/N in field-blended data and in deblended field-blended data is a factor of $\sqrt{M}$ larger than in the other cases.
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INFLUENCE OF RECORDING TIME

The improvement in the S/N of deblended field data with respect to unblended field data can also be understood by realizing that in blended acquisition the source wavefield is incoherent. This means that the incoherent source power (total signal energy divided by recording time $T$) increases with the square root of the blending fold ($\sqrt{M}$). However, the source power can also be increased by keeping the number of sources equal and making the effective survey time shorter (Figure 7). If we do both, increasing the number of sources and decreasing the effective survey time, then the S/N of the deblended field records increases linearly with $\sqrt{BPI}$. This important property is illustrated in Figure 8.

Figure 7: The source power (total signal energy divided by survey time) can be increased by increasing the number of sources while keeping the effective survey time the same (a). The source power can also be increased by keeping the number of sources equal and making the effective survey time shorter. In both situations the background-related noise power is the same.

CONCLUSIONS

In field blending, the power of the background noise is independent of the blending process (thus also of the blending fold). In computer blending, the power of the background noise increases with the blending fold.

For a given survey time, the background-related S/N in the deblended shot records increases with increasing blending fold ($\sqrt{N_s/N_s'}$). Moreover, for a given blending fold the background-related S/N increases with decreasing effective survey time ($\sqrt{T/T'}$). By combining the two, the background-related S/N of deblended field data increases with the square root of the blending performance indicator ($\sqrt{BPI}$).

Decreasing the effective survey time is not only an economic benefit, it is also a benefit with respect to data quality. The limit in decreasing survey times is given by the incoherency requirement of the blended source wavefield.

By simulating blended shot records in the computer (numerical blending), deblending gives an under-estimate of the benefit of blending.

Blending is not only an excellent solution for situations with a high background noise (same S/N is realized with higher noise levels), it also offers an attractive solution to cope with the increasing legislation on sea life protection (same S/N is realized with lower signal levels). In addition, blending offers a major benefit in areas where access is only possible for a very limited period of time.

FINAL REMARK

If we analyze blended seismic data after migration, then a second improvement of the S/N ratio can be observed due to the improved source sampling (resulting in less aliasing noise). Both properties of field blending, more source power and better source sampling, explains the large increase in image quality that can be seen in practice. As a consequence, we expect that unblended seismic acquisition will become a technology of the past.

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EDITED REFERENCES

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REFERENCES


