We_R01_03

Methodology Utilizing Continuous Source and Receiver Wavefields - Signal to Noise Ratio Considerations

S. Hegna[1]*, T. Klüver[1], J. Lima[1]

[1] PGS

Summary

The peak sound pressure levels (SPL) and the sound exposure levels (SEL) are significantly reduced with the seismic methodology based on the emission and recording of continuous source and receiver wavefields. The peak sound pressure levels are reduced because the emitted energy is spread out in time approaching the properties of white noise, in contrast to conventional marine sources where the emitted wavefield is approaching the properties of a spike. The energy levels emitted by marine seismic sources and its impact on the signal to noise ratio has been discussed in a number of papers. The ability to achieve comparable penetration in depth with the continuous wavefield method despite of significantly reduced peak SPL and SEL levels compared to the conventional marine seismic method is related to several aspects such as attenuation of shot generated noise, improved spatial sampling of source positions, and improved ability to attenuate noise with long continuous records. In this paper we will discuss the phase spectrum of the wavefield emitted by a source, and its influence on the signal to noise ratio after deconvolving the emitted wavefield from the received wavefield.

Introduction

A novel seismic methodology based on the emission and recording of continuous source and receiver wavefields has been developed (Hegna et al., 2018a; Klüver et al., 2018). One of the main objectives is to reduce the potential environmental impact of marine seismic acquisition. This can be achieved by distributing the emitted energy in time. The desired signal for the continuous wavefield methodology is band-limited white noise, i.e. a flat amplitude spectrum over a desired bandwidth and a randomized phase spectrum. Existing hardware on-board seismic vessels can be used to approach the properties of white noise by triggering individual air-guns with short randomized time intervals. A field trial conducted offshore Brazil using continuous wavefields shows that the peak sound pressure levels (SPL) are reduced by 20-22 dB compared to seismic data acquired in the same area with a conventional source array, and that the sound exposure levels (SEL) are reduced by 8-9 dB (Hegna et al., 2018b).

Figure 1 shows data from the field trial with a comparison between one inline from the conventional data set and the data acquired and processed using continuous wavefields after 3D migration. Despite the fact that the peak SPL and SEL levels are significantly reduced compared to the conventional data, the signal penetration at depth is comparable. The ability to achieve comparable penetration with significantly reduced peak SPL and SEL levels using continuous wavefields is related to several aspects such as attenuation of shot generated noise, improved spatial sampling of source positions, and improved ability to attenuate noise with long continuous records. In this paper we will focus on another aspect; the phase spectrum of the signals emitted by a source, and its influence on the signal-to-noise ratio after deconvolving the emitted wavefield from the received wavefield.

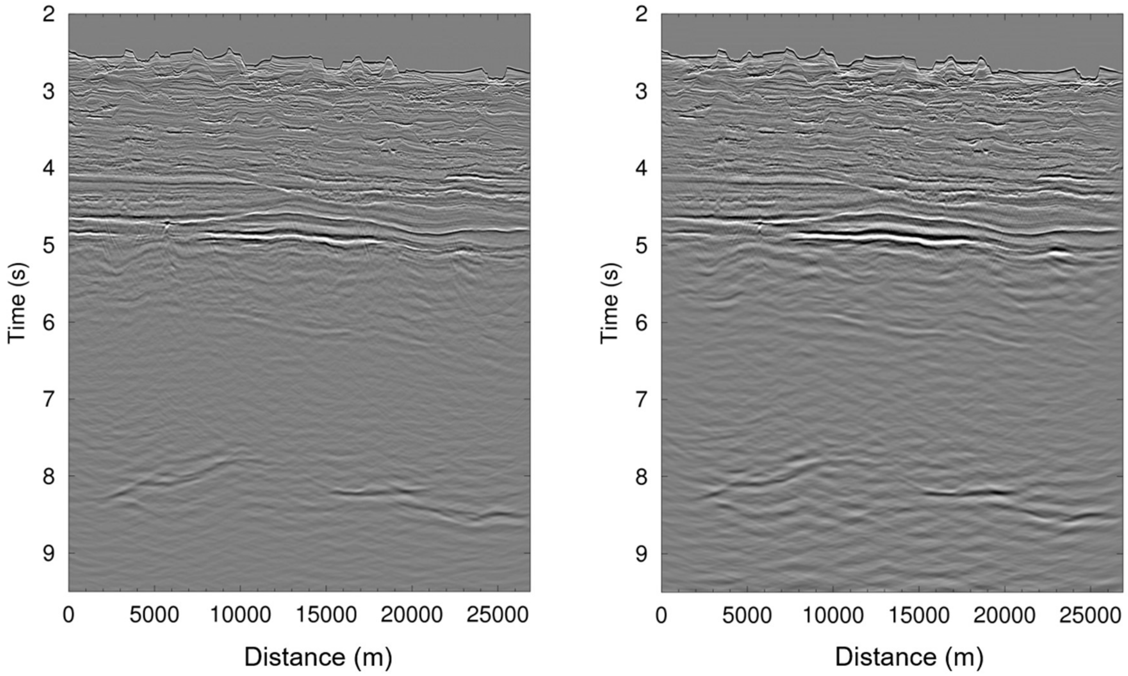

Figure 1 *Conventional dual source data (left), and data acquired with the continuous wavefield methodology (right).*

Influence of the phase spectrum

The energy levels emitted by marine seismic sources and its impact on the signal to noise ratio has been discussed in a number of papers, e.g. Laws et al. (2008) and Kragh et al. (2012). There less attention has been paid to the phase spectrum of the emitted source wavefield. Traditional marine seismic source arrays have been operated by triggering many air-guns simultaneously generating large peak sound pressure levels. The source arrays have been designed such that the primary–to-bubble ratio is maximized by combing air-guns and clusters of air-guns of different volumes in different positions. By this means source arrays have been designed to emit a wavefield approaching the properties of a spike. Since the phase spectrum of a spike is zero, the phase spectrum of the emitted wavefield from conventional source arrays has had limited influence. When utilizing continuous source and receiver wavefields, a source can emit signals continuously whilst moving. In order to permit a stable deconvolution of a continuously emitted wavefield, the desired signal would be band limited white noise with a randomized phase spectrum. In order to extract the response of the earth from the recorded seismic data, the wavefield emitted by the source has to be deconvolved. This is a multi-dimensional deconvolution of the complete wavefield emitted by a source contributing to a receiver location. In order to illustrate the difference between deconvolving signals approaching the properties of a spike, as with conventional marine seismic sources, and signals approaching the properties of white noise, as with the continuous wavefield methodology, a one-dimensional numerical experiment will be shown. The signatures (wavelets) used for the experiment, and the construction of the traces used in the deconvolution will be described below. Following this, the deconvolution results of the different signatures from the constructed traces will be discussed.

A ghost-free far-field signature from a conventional source array is used as a reference signature (upper graph in Figure 2). A second signature (lower graph in Figure 2) has been constructed from the amplitude spectrum of this far-field signature, and combined with a randomized phase spectrum. This wavelet is constructed such that it is limited in time to 12.5 seconds by applying a windowing function, and scaled such that the total energy is similar to the original far-field signature. The main difference between the two wavelets is therefore the phase spectrum.

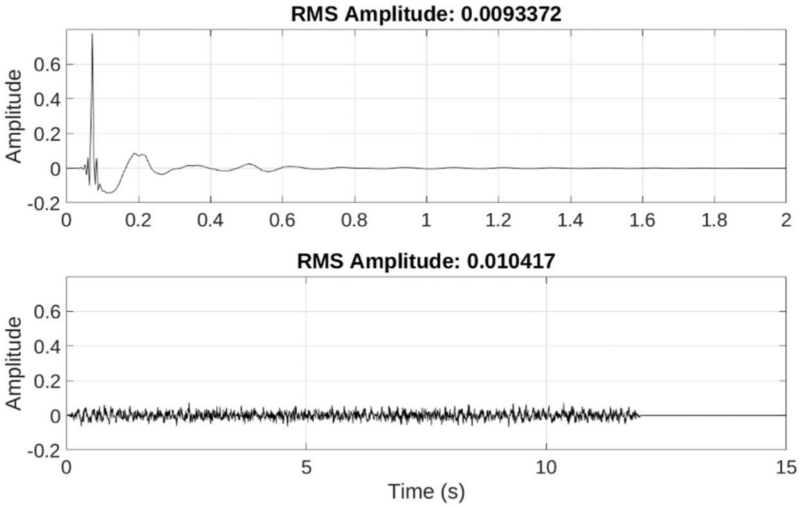

***Figure 2** Far-field signature for a conventional source array (upper graph) and a signature extended in time (lower graph) constructed by combining the amplitude spectrum of the conventional far-field signature with a randomized phase spectrum followed by an inverse Fourier transform, application of a windowing operator and a scalar.*

The traces used for the deconvolution experiment shown in Figure 3 have been constructed by creating a band limited reflectivity series (trace 1). In addition, a noise trace has been created with an amplitude spectrum that is inversely proportional to frequency multiplied by a band-pass filter, and with a randomized phase spectrum. The second trace in Figure 3 shows the sum of the band-limited reflectivity series and the noise. The third and the fourth traces in Figure 3 show the convolution of the far-field signature with the reflectivity series plus the noise, and the convolution of the signature with the randomized phase spectrum with the reflectivity series plus the noise respectively. Therefore, the only difference between the third and the fourth trace in Figure 3 is the signature that is convolved with the reflectivity series.

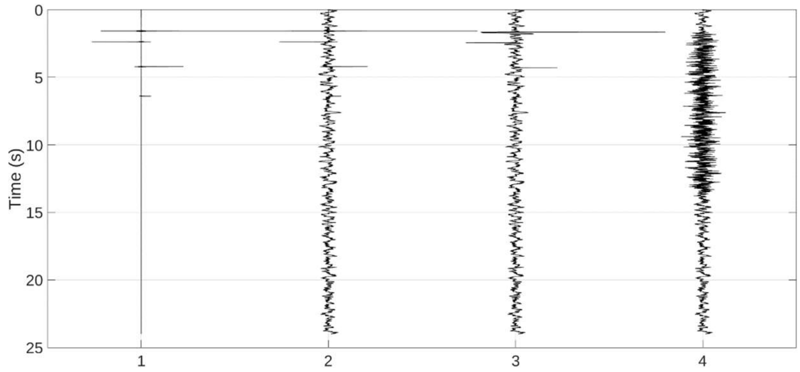

Figure 3 Band-limited reflectivity series (trace 1), the reflectivity series plus noise (trace 2), far-field signature from conventional array convolved with the reflectivity series plus noise (trace 3), signature with randomized phase spectrum convolved with the reflectivity series plus noise (trace 4). The same noise has been added in traces 2, 3 and 4.

Figure 4 shows the deconvolution results that will be discussed below. The first and the second traces in Figure 4 show the results after devonvolving the far field signatures shown in Figure 2 from the third and the fourth traces shown in Figure 3. The first trace with the results after deconvolving the far-field signature from trace 3 in Figure 3 shows that the noise is only slightly affected by the deconvolution because the signature approaches the properties of a spike. Since the amplitude levels in a typical far-field signature are reduced towards lower frequencies, the noise is amplified by the deconvolution in the low frequency end. The second trace in Figure 4 shows the results after deconvolving the signature with the randomized phase spectrum from the fourth trace in Figure 3. In this case the noise is significantly affected by the deconvolution, and looks very different from the original noise. The reason for this is the phase spectrum of the wavelet that has been used for the deconvolution. Especially in the later parts of the trace after the deconvolution the noise levels are reduced compared to the original noise levels. The reason for this amplitude reduction is that the noise is spread out in time according to the wavelet used for the deconvolution. In order to achieve this effect in the deconvolution process, it is important to extend the traces in time by zero-padding in order to allow for signals to be spread outside the original time window of the input traces.

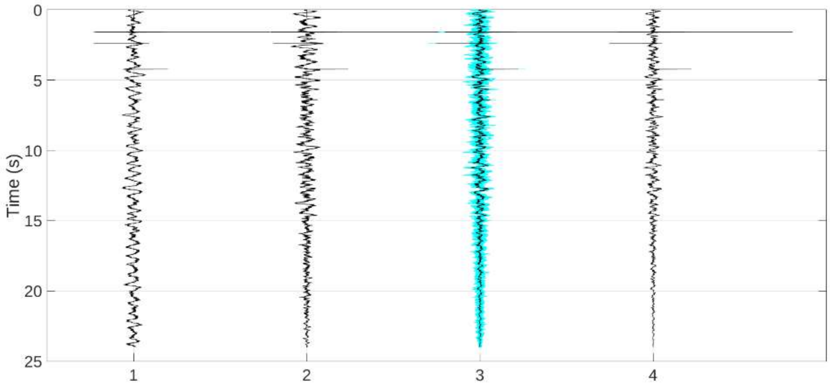

Figure 4 *Deconvolution result of conventional far-field signature from trace 3 in Figure 3 (trace 1), deconvolution result of signature with randomized phase spectrum from trace 4 in Figure 3 (trace 2), deconvolution results of 10 different realizations of signatures with randomized phase spectra in cyan with the mean of those 10 traces on top in black (trace 3), and the same mean of the 10 traces repeated (trace 4).*

When emitting a continuous wavefield that is approaching the properties of white noise, in other words signals that are changing all the time, coherent noise will become randomized by the properties of the source wavefield. This is different from conventional marine seismic acquisition where source arrays are emitting similar wavefields in every shot. To illustrate the effect of changing the emitted signals all the time on coherent noise, ten different realizations of the signature with a randomized phase spectrum have been created and convolved with the reflectivity series, the same noise as before has been added to all 10 traces. Finally the ten wavelets have been deconvolved from the constructed traces. The ten deconvolution results are plotted in cyan under trace 3 in Figure 4. Because the wavelets used for the deconvolution are different for each of the ten traces, the resulting noise after the deconvolution is different for all as shown by the curves in cyan. The black curve on top of the cyan curves and also plotted as a fourth trace in Figure 4 shows the stack of the ten deconvolution results. Because the same noise ends up different in each deconvolution result whereas the signal end up the same, the signal to noise ratio in the trace after stacking the ten deconvolution results is improved compared to the individual results.

Conclusions

With the continuous wavefield methodology introduced by Hegna et al. (2018a) and Klüver et al. (2018), the signal penetration at large depths are similar to conventional data as illustrated in Figure 1 despite the fact that the SPL and SEL levels are significantly lower compared to the conventional data. For the data shown in Figure 1, the peak SPL is reduced by 20-22 dB and SEL is reduced by 8-9 dB (Hegna et al., 2018b). There are several factors contributing to this achievement. In this paper we focus on the phase spectrum of the emitted source wavefield, and have illustrated in a one-dimensional numerical experiment how noise is affected by the phase spectrum of the signature in the deconvolution step. There are two main conclusions we can draw from this experiment. Firstly, when deconvolving a signature with a randomized phase spectrum, the noise is highly affected due to the phase spectrum of the signature. The noise levels in the later parts of the trace after the deconvolution are reduced due to the fact that the noise will spread outside the time window where live data exists when deconvolving the signature. This contributes to the deep penetration. The second conclusion we can draw from this numerical experiment is that when simulating ten different realizations of the signature with a randomized phase spectrum and deconvolving these from ten traces containing the same noise, the noise in each trace is very different after the deconvolution. In the numerical experiment the noise is assumed to be perfectly coherent, which is never the case in reality. However, the experiment shows that any noise with some coherency before the source deconvolution step ends up less coherent after this step and will be attenuated after summation of multiple traces as e.g. in the migration of the seismic data.

Acknowledgements

We thank PGS for permission to publish this paper, and Equinor and The Research Council of Norway for funding the project together with PGS.

References

Hegna, S., Klüver, T. and Lima, J. [2018a] Making the transition from discrete shot records to continuous wavefields - Methodology. 80th *Conference and Exhibition, EAGE,* Extended Abstracts, We A10 03.

Hegna, S., Klüver, T., Lima, J. and Asgedom, E. [2018b] Latest field trial confirms potential of new seismic method based on continuous source and receiver wavefields. *First Break,* **36** (11), 83–88.

Klüver, T., Hegna, S. and Lima, J. [2018] Making the transition from discrete shot records to continuous wavefields – Real data application. 80th *Conference and Exhibition, EAGE,* Extended Abstracts, We A10 04.

Kragh E., Laws, R. M., Hopperstad, J.F. and Kireev A. [2012] Reducing the size of the seismic source with a 4C towed-marine streamer. 74th *Conference and Exhibition, EAGE,* Extended Abstracts, Z014.

Laws, R. M., Kragh E. and Morgan G. [2008] Are Seismic Sources Too Loud? 70th *Conference and Exhibition, EAGE,* Extended Abstracts, B026.