Latest field trial confirms potential of new seismic method based on continuous source and receiver wavefields

Stian Hegna[1*], Tilman Klüver[1], Jostein Lima[1] and Endrias Asgedom[1] describe a new marine seismic method based on emitting and recording of continuous source and receiver wavefields that significantly reduce both sound pressure levels and sound exposure levels.

Introduction

eSeismic is a novel seismic methodology based on the emission and recording of continuous source and receiver wavefields. One of the motivations behind developing the methodology has been the increased focus on the potential environmental impact of marine seismic acquisition, which the new methodology seeks to reduce. A particular focus has been placed on the peak sound pressure levels emitted from seismic sources and their potential impact on marine mammals and fish with swim bladders. Consequently, authorities across the world have started to introduce stronger regulations concerning the use of seismic sources. The industry has responded by engaging in the development of marine vibrator systems that emit lower-amplitude transient signals and hence are expected to comply with stricter environmental regulations. Different marine vibrator systems are currently being developed or tested but none have reached full-scale commercial readiness.

The methodology described in this paper has not been developed with any specific marine source technology in mind. The desired signal for the outlined methodology is that of white noise, as this enables deconvolution of the data with the total source wavefield. Indeed any type of mechanical device that produces a source signal that approaches the properties of white noise can be utilized in the eSeismic method. As described later, existing air gun equipment used on board modern seismic vessels has been used to generate the results discussed here and is equally suited for this method as are any marine vibrator systems of the future.

Another motivation for developing the proposed new methodology was the desire to improve acquisition efficiency and/or improve the source side sampling. To address both these aspects of marine seismic acquisition, the industry has been developing simultaneous source technologies over the last couple of decades. However, since traditional seismic acquisition methods generate individual wavefields in each shot location, a deblending step is required in order to reconstruct such wavefields for the purpose of forming an artefact-free subsurface image. The methodology we propose in this article is fundamentally different in that individual wavefields at discrete shot locations are not considered. Instead, what is emitted by one or more source elements as a function of time and lateral position is treated as one continuous wavefield. Hence, there is no need for deblending in the method presented here.

In addition to these improvements, the methodology also offers flexibility in realizing possible acquisition configurations.

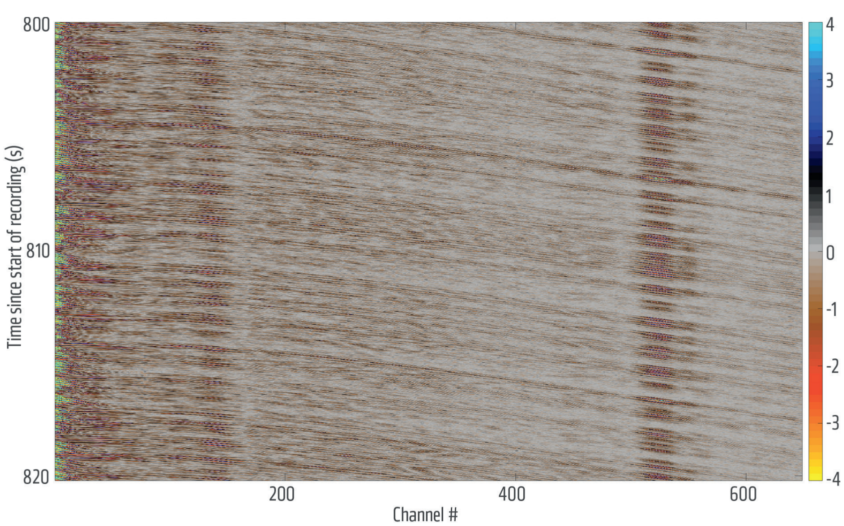

Figure 1 A 20-second portion of a continuous seismic record with raw hydrophone data, with signals generated by triggering individual air guns with short randomized time intervals.

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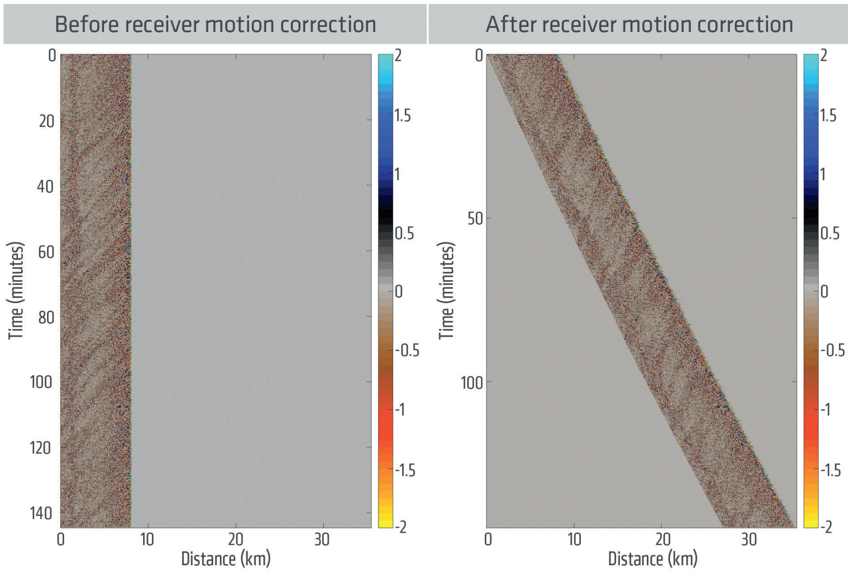

Figure 2 One continuous seismic record from one sail line before and after correcting for the receiver motion. Each data trace after receiver motion correction represents one stationary receiver location.

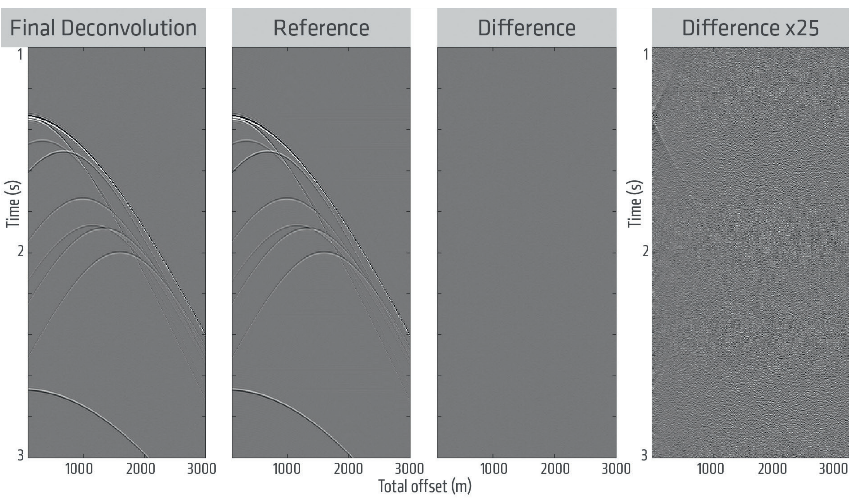

Figure 3 Final deconvolution result of a continuous synthetic receiver trace in a stationary location (first panel to the left), the desired result (second panel from the left), the difference between the actual result and the desired result (third panel from the left), and finally the difference multiplied by a factor 25 (fourth panel from the left).

In this paper, we will describe the basic principles behind the methodology, and discuss the results from a small field trial conducted offshore Brazil in May/June 2018.

Acquisition methodology

The seismic methodology presented here is based on continuous source and receiver wavefields (Hegna et al., 2018; Klüver et al., 2018). This means that the seismic data are recorded continuously for as long as it takes to acquire a given sail line. It also means that sources operate continuously. The ideal continuous wavefield to be emitted from a source using this methodology would be white noise, band-limited to achieve a desired maximum bandwidth in the final images. In order to be able to use the method without having to make significant hardware changes onboard today's seismic vessels, a source configuration and triggering scheme of individual airguns has been designed such that the emitted signals are approaching the properties of white noise. Individual air guns are triggered in a near-continuous fashion with short randomized time intervals, generating a continuous wavefield. The triggering of the individual airguns is based on time only and not their respective position. Hence, the mean time interval between consecutive air gun firings is the same regardless of vessel speed. Figure 1 shows a 20-second portion of a continuous seismic record with seismic signals recorded when individual air guns are triggered in the fashion described above.

Since both the seismic recording and the sources are operated based on time, the seismic acquisition method as such is not a limiting factor in terms of vessel speed in the same way as for conventional methods. In addition to continuous seismic recording, near-field hydrophone data needs to be recorded continuously in order to be able to determine the exact wavefield emitted by the individual source elements.

Imaging with continuous wavefields

On the receiver side, all the continuous data is processed at once, and treated as a continuous data set. Pre-conditioning of the data, such as corrections for sensor responses and noise attenuation, is applied to the entire continuous data set to ensure that the continuity of the data is maintained. Before separating the wavefields recorded by multi-component streamers into up- and down-going wavefield components, the lateral motion of the receivers needs to be taken into account. This is done by putting the data samples into the locations along the line trajectory where they were received. By doing so a large data matrix is constructed where the live data fall in a band along the diagonal. Figure 2 illustrates continuous seismic data from one sail line before and after correction for receiver motion. The temporal length of the resulting data matrix is given by the time it took to acquire the sail line, and the spatial extent is determined by the length of the sail line along its trajectory plus the streamer length. After the receiver motion correction, each data trace represents a stationary receiver location relative to the geology to be imaged, and the temporal extent of the live data in each stationary receiver location is related to the vessel speed and the streamer length. As an example, if the vessel speed is 2 m/s and the streamer length is 8000 m, the temporal length of the live data in each stationary receiver location is 4000 s.

After receiver motion correction of each measured component, the wavefield separation can be performed where multi-component streamers have been used. The only difference from standard wavefield separation (Carlson et al., 2007) is that it is performed on the continuous data record at once. If streamer depth variations need to be corrected for in a redatuming step, these depth variations are also handled in a continuous fashion. Such depth variations typically occur very gradually along the line, and this smoothness is maintained when the corrections are performed in a continuous fashion on the complete data record.

Once the recorded seismic data for each stationary receiver position have been prepared, the deconvolution of the emitted source wavefield can be performed. This is done by computing the entire emitted source wavefield that can conceivably contribute to a given stationary receiver location. In order to enable a stable deconvolution of the source wavefield, the wavefield itself needs to be as white as possible without deep notches in the spectrum. The main challenge with deconvolving a continuous source wavefield from a continuous receiver trace in a given stationary receiver location is that there is no information about the source emission angles in the recorded data. To perform the required angle-dependent deconvolution of the emitted source wavefield, all possible source emission angles need to be considered during the deconvolution process. An iterative source deconvolution method has therefore been developed where coherent signals associated with the response of the earth are extracted in each iteration. The extracted signals are accumulated during the iterations. In each iteration the modelled contributions of the extracted signals to the receiver trace are subtracted from the original receiver trace, and the source wavefield is deconvolved from the residual receiver trace to create residual receiver gathers from which coherent signals are extracted. Figure 3 shows a result after deconvolving a continuous source wavefield from a synthetic stationary receiver trace where the synthetic data

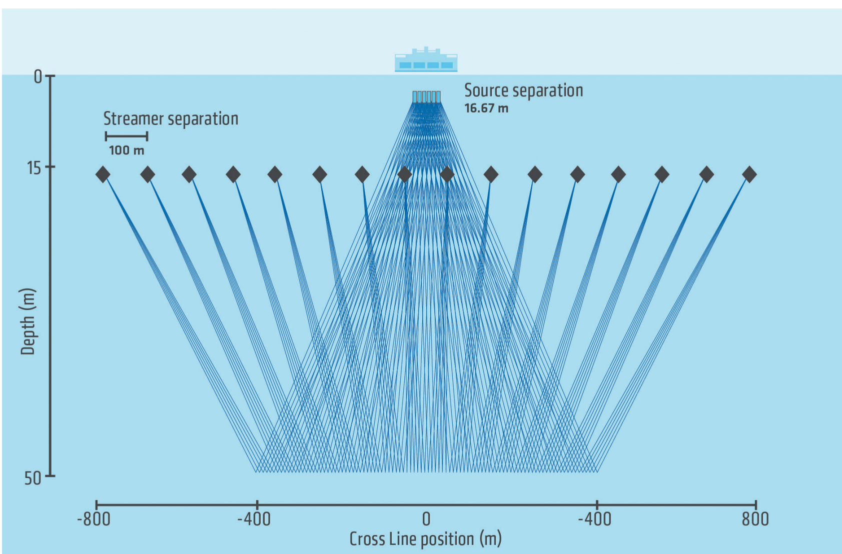

Figure 4 Illustration of the acquisition configuration cross-line used for the 3D test survey.

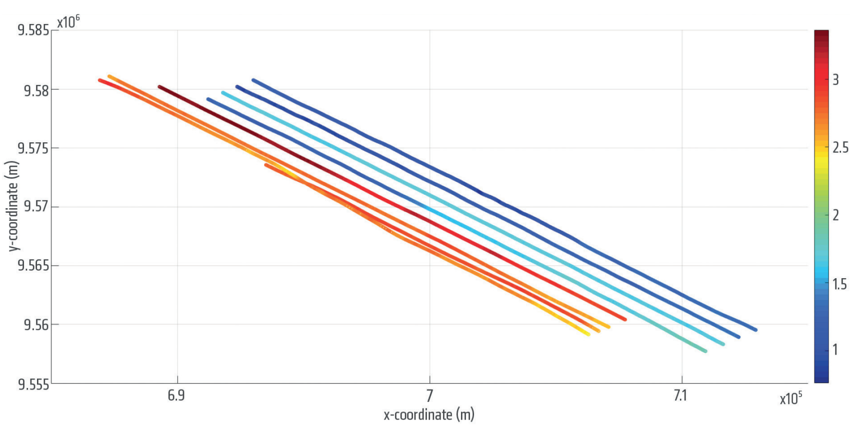

Figure 5 Vessel locations for the field trial with bottom speed shown in colour.

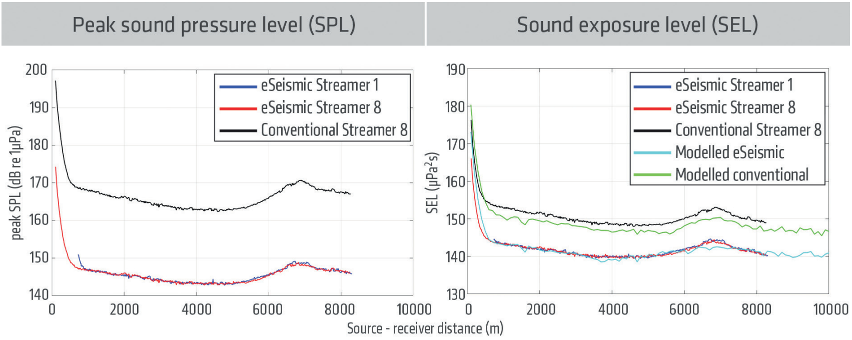

Figure 6 Peak sound pressure levels (SPL) to the left, and sound exposure levels (SEL) to the right.

has been derived based on a source emitting band-limited white noise signal.

The result of the source deconvolution form common receiver gathers. Provided that the emitted source wavefield is a continuous or near-continuous wavefield, the trace spacing within the resulting common receiver gathers can be chosen during processing. The common receiver gathers are also fully anti-alias protected according to the selected trace spacing. In essence, the locations of the output traces can be anywhere along the trajectories where source elements have been located during the acquisition. This means that if six strings with airguns are towed behind a seismic vessel, each emitting a continuous or near-continuous wavefield, it is possible to output six common receiver gathers one in each cross-line position of the strings.

A small-scale seismic experiment — data acquisition

A small eSeismic field trial has been performed offshore Brazil. The goal of the field trial was to validate the design of the source, ensure that existing imaging algorithms can be used and prove that despite a substantial reduction in the SPL and SEL, the subsurface penetration is sufficient. The test data was acquired with 16 8100 m-long multi-component streamers with 100 m inter-cable spacing. The streamer depth was 15 m. The source set-up consisted of six strings with airguns. Each string was equipped with six airguns. Individual airguns were triggered with short randomized time intervals. The mean interval between consecutive triggerings was approx 290 ms. A 20 s portion of a continuous seismic record from this survey is shown in Figure 1. The nominal distance between the strings of the airguns array was 16.70 m. Since the source deconvolution described in this publication can solve for one point source per string of airguns (i.e. six point sources in the cross-line direction) the nominal cross-line bin size for this survey was 8.33 m. The dense cross-line CMP spacing was achieved without compromising acquisition efficiency. A ~800 m swathe was covered by each sail line, which is similar to the coverage achieved with a standard flip-flop source configuration and a similar streamer configuration. However, each 800 m swath contained 96 CMP lines with the new method compared to 32 CMP lines with a standard flip-flop configuration. A front/tail view illustrating the increased cross-line sampling is shown in Figure 4.

One interesting aspect of this pilot survey was the presence of strong currents in the area during the acquisition, and the

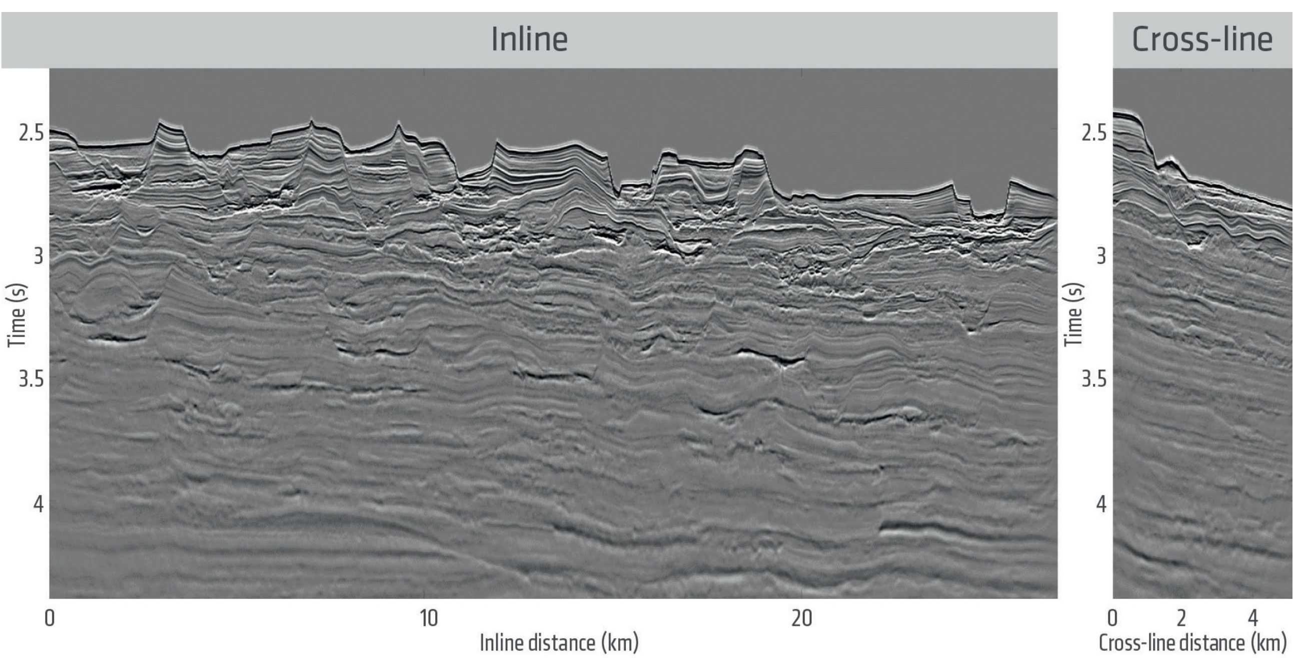

Figure 7 An in-line and a cross-line from preliminary migrated results of the field trial. Data shows high structural detail, especially in the shallow part of the section and great lateral resolution across the whole of the section.

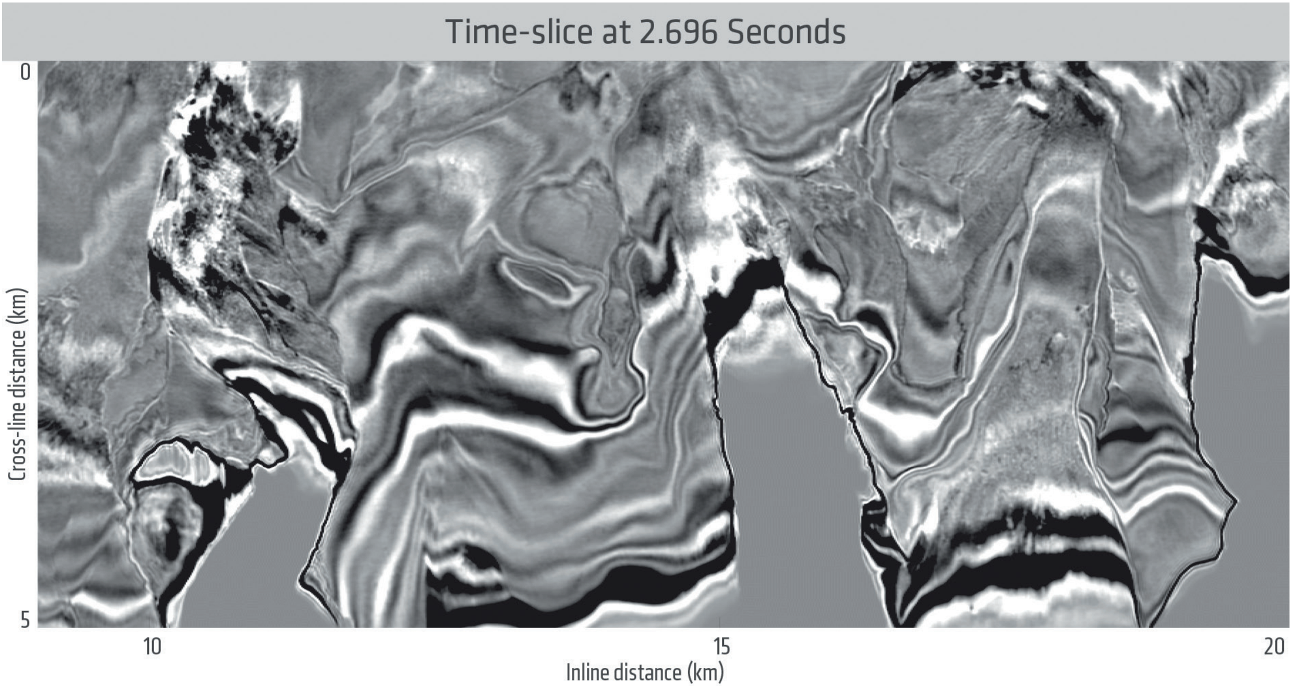

Figure 8 A time-slice from preliminary migrated results of the field trial survey demonstrating high signal-to-noise levels and the ability of the proposed novel acquisition method to resolve fault boundaries in great detail, aided by the significant increase in spatial source sampling.

impact these currents had on the bottom speed. Half of the sail lines were acquired against the currents with a bottom speed down to ~2 knots. In the opposite direction the bottom speed was reaching a maximum of ~6.5 knots (Figure 5). Since shots are triggered solely based on time and are independent of the actual source location the vessel speed did not have to be reduced when sailing with the currents using the new eSeismic method.

One of the anticipated benefits of using the proposed method is the potential reduction in environmental impact. The peak sound pressure levels are substantially reduced by triggering one airgun at a time compared to triggering many airguns in an array simultaneously, as is the case in conventional marine seismic sources. Sound exposure levels are also reduced. Figure 6 shows a comparison between sound pressure levels (SPL) and sound exposure levels (SEL) derived from the recorded hydrophone data from the 3D small-scale pilot survey and data acquired in the same area using conventional methods with the same streamer configuration. The peak sound pressure levels are approximately 20-22 dB lower for the new method whereas the sound exposure levels are 8-9 dB lower when compared to the conventional acquisition method.

In addition to comparing sound exposure levels as derived directly from the recorded seismic data, SEL values were also modelled by estimating the emitted acoustic wavefield from the seismic source(s) and combining this with modelling the propagation of the wavefield. The acoustic energy can then be calculated at any given location to give a measure of the SEL. The propagation modelling approach used here was based on solving the parabolic wave equation and taking into account bathymetry, sediment properties and sound speed profile in the water column. The modelled SEL values fit the differences determined from the measured data reasonably well (Figure 6).

A small-scale seismic experiment — data examples

As described above, as a result of the deconvolution of the continuous source wavefield, it is possible to output one point source per string of airguns resulting in a hexa-source configuration for the source set-up described in this publication. This means that the spacing for each of the six-point sources is 12.5 m along the line direction. In total, this results in 12 times more data compared to a conventional flip-flop acquisition with a similar streamer configuration. Each of the common offset planes is regularized to 8.33 x 8.33 m bin size, and anti-alias protected for 12.5 x 12.5 m bin size to anti-alias protect the input to the migration. The output from the 3D migration has a 12.5 x 12.5 m bin size. An inline and cross-line example of the migrated data is shown in Figure 7, and a time-slice in Figure 8.

Summary and conclusions

We have introduced a new marine seismic method that treats the wavefields on both the source and the receiver side as continuous. The method requires seismic data to be recorded continuously and the source signals to be emitted uninterrupted while moving. An ideal continuous source wavefield should be as white as possible, both in a temporal and in a spatial sense, to avoid deep notches in the spectrum and to aid the multi-dimensional deconvolution. In order to generate such an ideal source wavefield using existing equipment individual airguns are triggered with short randomized time intervals in a near-continuous fashion.

One of the main potential benefits with the proposed method is reduced environmental impact of marine seismic sources. The peak sound pressure levels are significantly reduced by triggering one airgun at a time compared to triggering many airguns in an array simultaneously as in conventional marine seismic sources. Sound exposure levels are also reduced. The peak sound pressure levels are approximately 20-22 dB lower for the proposed method compared with conventional methods, whereas the sound exposure levels are 8-9 dB lower for eSeismic data. Dense cross-line CMP spacing is achieved without compromising the acquisition efficiency. The 800m-wide sail-line is sampled with 96 common mid-points compared to 32 with a standard dual-source configuration. From an efficiency standpoint, there are minimal vessel speed limitations since this method does not require the seismic recording or the sources to be triggered with specific spatial intervals. Limitations imposed by shot cycle time and record length are now relaxed.

Real data examples show that high-resolution seismic images can be produced from seismic data acquired and processed using the proposed method.

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