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# Making the transition from discrete shot records to continuous seismic records and source wavefields, and its potential impact on survey efficiency and environmental footprint

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## ABSTRACT

A marine seismic method based on continuous source and receiver wavefields has been developed. The method requires continuous recording of the seismic data. The source that may consist of multiple source elements can emit signals continuously while moving. The ideal source wavefield to be used with this method should be as white as possible both in a temporal and a spatial sense to avoid deep notches in the spectrum enabling a stable multi-dimensional deconvolution. White noise has such properties. However, equipment that can generate white noise does not exist. In order to generate a continuous source wavefield that is approaching the properties of white noise using existing equipment onboard marine seismic vessels, individual air-guns can be triggered with short randomized time intervals in a near-continuous fashion. The main potential benefits with the method are to reduce the environmental impact of marine seismic surveys and to improve acquisition efficiency. The peak sound pressure levels are significantly reduced by triggering one air-gun at a time compared to conventional marine seismic sources. Sound exposure levels are also reduced in most directions. Since the method is based on continuous recording of seismic data and the air-guns are triggered based on time and not based on position, there are less vessel speed limitations compared to conventional marine seismic data acquisition. Also, because the source wavefield is spread out in time, the wavefields emitted from source elements in different cross-line positions can be designed such that the emitted wavefield is spatially white in this direction. This means that source elements in multiple cross-line positions can be operated simultaneously, potentially improving the cross-line sampling and/or the acquisition efficiency.

## INTRODUCTION

Traditionally, marine towed streamer seismic data recording is triggered such that it starts shortly before or at the time when the sources are triggered. The length of the records in time has been defined such that it is less than the time it takes to move the vessel from one source position to the next. Consequently, the recording time was decreasing with decreasing shot point interval. Therefore, minimum shot spacing and maximum vessel speed, i.e. source side sampling and acquisition efficiency, have been limited by the required record length. The triggering of the seismic sources has been based on position with a predefined constant shot point interval, and the triggering of the recording system has been synchronized accordingly.

In order to maximize the recording time after the source(s) stop emitting signals, sources have been designed to emit a wavefield that approaches a spike. The trend over several years has been to increase the strength of the marine seismic sources, and hence the peak pressure levels of the emitted energy, in order to maximize the signal-to-noise ratio in the seismic data. This has resulted in large arrays of air-guns triggered simultaneously. High sound pressure levels increasingly result in environmental restrictions for seismic acquisition.

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With the advent of continuous recording, seismic data are acquired continuously from the receivers. Onboard the vessels, the data are typically split up into records of finite lengths that may be overlapping, at times related to trigger times of the source(s). However, the sources are still triggered by position with a specific spacing and minimum time interval. Because the sources are triggered by position with a minimum listening time, the shot spacing is typically large compared to the receiver spacing and the maximum vessel speed is limited. In order to increase the efficiency and/or shot density, various blended or simultaneous source techniques have been proposed (e.g. Beasley, Chambers and Jiang 1998; Berkhout 2008; Frømyr *et al.* 2008; Mueller *et al.* 2016; Robertsson, Amundsen and Sjøen Pedersen 2016; Sjøen Pedersen, Amundsen and Robertsson 2016). Since these methods are still based on discrete shot records, a 'de-blending' is needed in order to construct such records.

Furthermore, in methods using encoded source sequences (Robertsson *et al.* 2012; Mueller, Robertsson and Halliday 2014; Mueller *et al.* 2016), 'the machine gun array' (Ziolkowski 1984) and 'Popcorn shooting' (Abma and Ross 2013), the signals emitted from the source(s) are spread out in time. This means that the peak sound pressure levels, i.e. the impact on the environment, can be reduced, and the correlation between wavefields emitted from multiple sources operated simultaneously can also be reduced. Marine vibrators have also been proposed in order to spread the emitted signals out in time to reduce the impact on the environment (e.g. Pramik *et al.* 2015). However, common to all the methods referred to above is that they are based on considering the wavefields associated with specific source locations or a small area around such locations as individual wavefields. If the received wavefields in these source locations are overlapping in time, a de-blending is needed.

The seismic method described in this paper treats the wavefields on both the source and the receiver side as continuous wavefields. On the receiver side, seismic data recorded continuously are treated over the full time-length, typically the length of a sail-line, at once. On the source side the emitted wavefield is also treated as a continuous wavefield. This means that the source that may consist of multiple source elements can emit signals continuously while moving. All signals emitted that can contribute to the received wavefield in a stationary location are considered as one large multi-dimensional source wavefield that is deconvolved to extract the response of the earth. The motivation behind the method is to reduce the environmental impact of marine seismic surveys, improve acquisition efficiency and to reduce the trace spacing in common receiver gathers. With this method the sound pressure levels can be reduced because the sound energy emitted from the sources can be spread out in time, no minimum listening time is needed, and the trace spacing in common receiver gathers can be chosen in processing and be much denser than with conventional methods. In addition, source elements in multiple cross-line positions can be operated simultaneously because the wavefield emitted can be designed such that it is spatially white in the cross-line direction. Any type of source device can be used with the proposed method, provided that the emitted signals have the desired properties.

## GENERAL METHODOLOGY

In modern marine seismic acquisition, data are typically recorded continuously for as long time as it takes to acquire a sail line. With the proposed methodology, the seismic data recorded continuously are treated over the full time length at once. After some pre-conditioning of the data, such as correction for sensor responses and noise attenuation, any motion of the receivers is corrected for (see Fig. 1). If the data are recorded in stationary receiver positions, e.g. by ocean-bottom nodes, this step is not necessary since the data are already in stationary receiver positions.

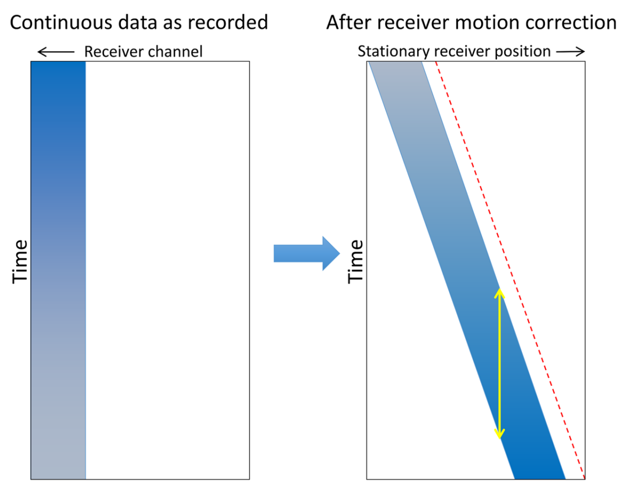


**Figure 1** The blue area to the left illustrates seismic data recorded continuously, with a temporal extent of a sail line, and a lateral extent corresponding to the streamer length. The blue area to the right represents the seismic data after receiver motion correction. The spatial extent of these data is the length of the sail line plus the streamer length. The red dashed line indicates the position of a source in front of the streamer as a function of time, and the yellow line represents the live data in a stationary receiver position with a temporal length of the streamer length divided by vessel speed.

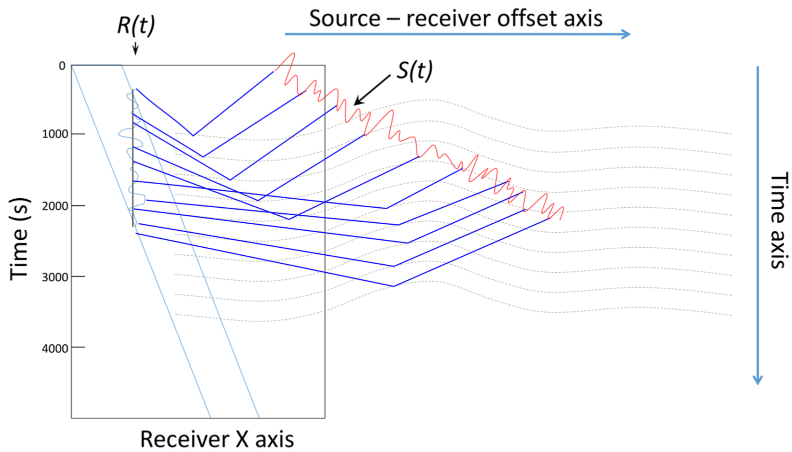


**Figure 2** $R(t)$ is a stationary receiver trace as a function of time, and $S(t)$ are the source signals emitted as a function of time in different offsets relative to the receiver location. The grey dashed lines represent one reflector in the sub-surface, and the blue lines represent some of the ray-paths from the source reflected at the sub-surface reflector and received in the stationary receiver position at selected times.

The receiver motion correction can be done based on the following equation:

$$R_m(t, k) = R(t, k)\mathrm{e}^{-ik\Delta x_r(t)}, \quad (1)$$

where $R$ and $R_m$ are the receiver data before and after receiver motion correction, $t$ is time, $k$ is the horizontal wavenumber and $\Delta x_r(t)$ is the lateral motion at time $t$. After the motion correction, the data are located in the positions where they were recorded as a function of time, representing stationary receiver positions.

After the receiver motion correction, recorded pressure and particle motion measurements can be split up into up- and down-going components (Carlson *et al.* 2007). Such a process is normally applied on a record by record basis. With the methodology proposed in this paper the wavefield separation is applied to the entire continuous data after receiver motion correction as one operation. Each trace in the resulting data set represents the separated wavefield in a stationary receiver location, and contains signals from all source–receiver offsets available for a given acquisition configuration as illustrated in Fig. 2. In typical towed streamer seismic with sources in front of the streamer spread, the time axis of the receiver trace also represents an offset axis as shown in the figure since the source moves away from the stationary receiver as time increases. Each reflector is illuminated from a range of source–receiver offsets and source emission angles throughout the time range of the receiver trace, as illustrated by the blue lines in Fig. 2.

A receiver trace in a stationary receiver location can be expressed by the following equation:

$$R(\omega) = \sum_n E(\omega, k_n)S(\omega, k_n), \quad (2)$$

where $R(\omega)$ is the received signals at angular frequency $\omega$, $E(\omega, k_n)$ is the response of the earth including all propagation effects and multiples at angular frequency $\omega$ and horizontal wavenumber $k_n$. The multi-dimensional source wavefield $S(\omega, k_n)$ contributing to the receiver location, including the source ghost, can be expressed as follows:

$$S(\omega, k_n) = \sum_t s(t)\mathrm{e}^{-i\omega t}\mathrm{e}^{-ik_n\Delta x_s(t)}\left(\mathrm{e}^{-ik_z z_s(t)} - \mathrm{e}^{ik_z z_s(t)}\right), \quad (3)$$

where $s(t)$ is the signals emitted from the source in a position $\Delta x_s(t)$ relative to the receiver location and at a depth $z_s(t)$ all at time $t$. The vertical wavenumber is represented by $k_z$.

The main challenge with deriving the response of the earth from equation (2) is that the receiver trace contains a superposition of many source emission angles, and these cannot be derived directly from the receiver trace. Therefore, an iterative source deconvolution method has been developed where all possible source emission angles are considered and where coherent signals associated with the response of the earth are extracted in each iteration. The extracted signals are accumulated during the iterations, 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 in each iteration to create residual receiver gathers from which coherent signals are extracted.

Because the method is based on retrieving common receiver gathers from a single continuous and stationary receiver trace, the source can, in principle, be a source that continuously emits signals while moving, provided that the emitted

 

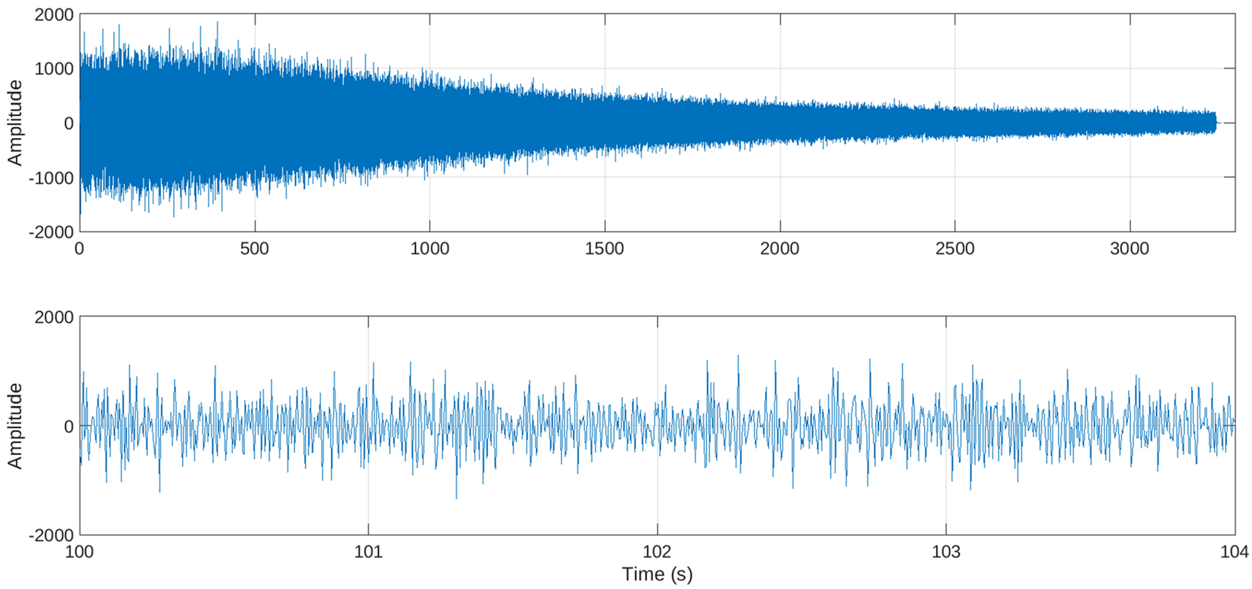


**Figure 3** Simulated receiver trace in a stationary position containing more than 3000 seconds of signals received continuously shown on top, and a 4 seconds portion of the receiver trace shown below.

signals are known. To illustrate this concept, a synthetic trace with a theoretical source emitting white Gaussian noise has been constructed using an earth model consisting of three reflectors and seven point diffractors. The synthetic common receiver trace is shown in Fig. 3.

The receiver trace shown in Fig. 3 and the source signals used to generate the synthetic trace were used as inputs to the iterative source deconvolution process. The results along with the desired output and the difference between the deconvolution result and the desired output are shown in Fig. 4.

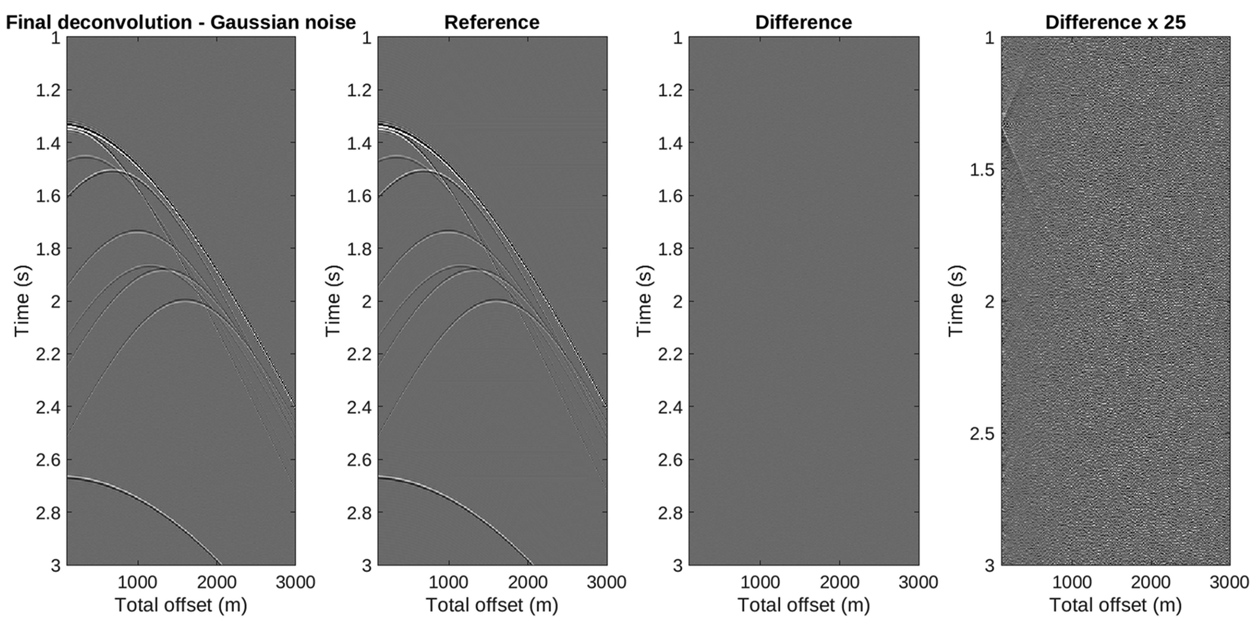


**Figure 4** Results from the iterative source deconvolution process shown to the left, using the white noise source signals and the receiver trace shown in Fig. 3 as inputs. The second image from the left shows the desired output, the third image from the left shows the difference between the deconvolution result and the desired result, and the image to the right shows the same difference multiplied by a factor 25.

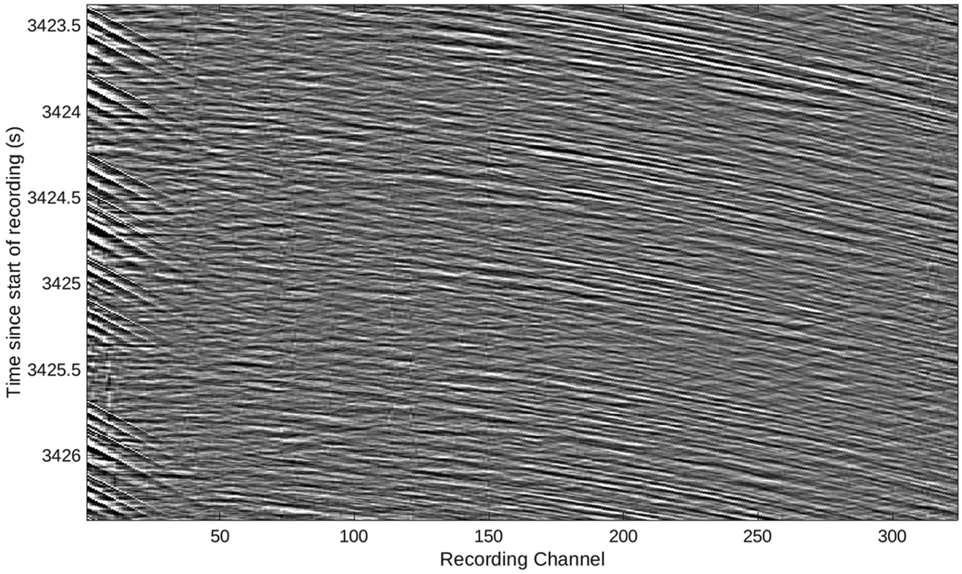


**Figure 5** Raw hydrophone data recorded continuously. The vertical axis is time since the start of the continuous recording. The horizontal axis is channel number along the streamer. The direct wavefield is visible in the front of the streamer on the left-hand side of the image, illustrating the density of the trigger times. In this data, example air-guns were triggered with a mean interval of 290 ms.

## DATA RECORDING

Since the method utilizing continuous source and receiver wavefields is based on time, the clocks on the different systems onboard the seismic vessel need to be accurately synchronized and refer to the same reference clock, e.g. the GPS clock. Time stamps referring to the same clock need to be available in all data that are recorded such that the times of the individual data samples can be determined with sufficient precision. Any triggering except for at the start of line and end of line can be based on time instead of position, which is different from conventional marine seismic acquisition.

At the beginning of a sail line, the seismic recording should start before the sources start emitting signals. The $x$, $y$, $z$ positions of the source elements as a function of time need to be known at all times during the seismic data recording. Therefore, the collection of source and receiver positions should start at the same time as the seismic data recording. The recording of seismic data as well as near-field hydrophone data should be continuous for the entire sail line. At the end of the line the sources should stop emitting signals in the order of 20 seconds before ending the seismic data recording and the collection of the source and receiver positions. The benefits of continuing the seismic recording for some time after the sources have stopped emitting signals are for the processing of the data to limit edge effects at the end of the line, and also for environmental monitoring. The decay of the pressure levels after stopping the seismic sources can be monitored, and the relative impact of the seismic activity can be estimated.

A portion of a continuous seismic record is shown in Fig. 5. The horizontal axis represents channel number along the streamer, and the vertical axis represents time since the start of the seismic data recording. Such continuous records are available for each sensor type, e.g. pressure and motion sensors, and for each streamer. The temporal length of the continuous record is the acquisition time of the sail line, which is typically in the order of some hours.

## GENERATING THE SOURCE WAVEFIELD

An ideal continuous source wavefield to be used with the method described in this paper should be as white as possible both in a temporal and spatial sense to enable a stable deconvolution of the source wavefield. White noise has such properties. However, equipment that can generate white noise does not exist. In order to generate a continuous source wavefield that is approaching the properties of white noise using existing equipment on-board marine seismic vessels, individual air-guns can be triggered with short randomized time intervals in a near-continuous fashion.

In order to approach the properties of white noise using air-guns, individual air-guns are triggered in a sequence such that the time interval between consecutive triggerings is as short as possible, given the technical constraints of the towed

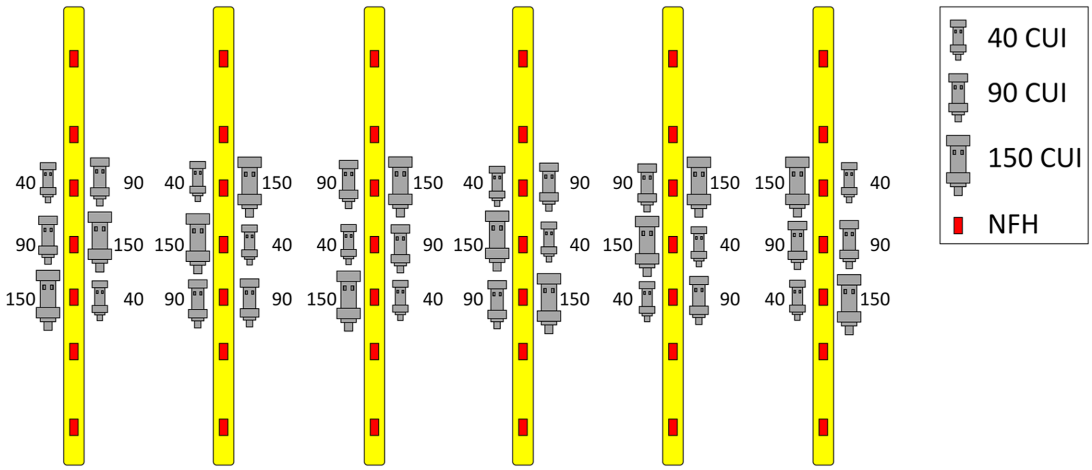


**Figure 6** Six strings with 40, 90 and 150 cubic-inch air-guns on each. The configuration of the three volumes is different on each sub-array to provide additional encoding of the wavefield emitted from each string. Locations of near-field hydrophones are indicated by red squares.

equipment. This order will have to be repeated at some point. However, the trigger times can be randomized all the time, so not repeated in any particular interval. In order to facilitate a stable deconvolution of the source wavefield, complementary bubble periods are necessary to mitigate the deep notches in the spectrum of the wavefield emitted from a single air-gun. Complementary bubble periods can be achieved by using air-guns of different volumes or by deploying the air-guns at different depths. If there is a need to correct for the effects of the source ghost beyond crossing the notch frequencies, it is beneficial to deploy the air-guns at different depths. Complementary bubble periods can in such cases be achieved by the differences in depth even if all air-guns are of the same volume. If the differences in depth are not sufficiently large to obtain complementary bubble periods, air-guns of different volumes can be used. Figure 6 illustrates a source configuration consisting of six air-guns on each string with three different volumes and with six strings of air-guns.

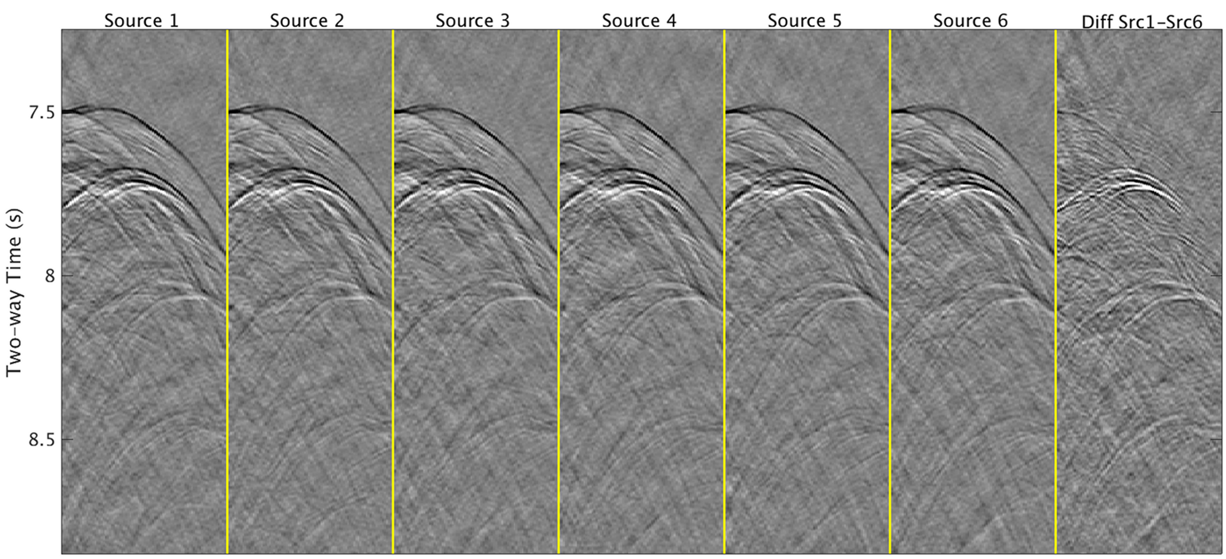


**Figure 7** Result of deconvolving the source wavefield into six common receiver gathers with earth responses extracted from one stationary receiver location based on data shown in Fig. 5 and the source configuration shown in Fig. 6. The spacing between the strings of air-guns was 12.5 m. The difference between the common receiver gather associated with source 1 and with source 6 is shown on the right hand side of the image.

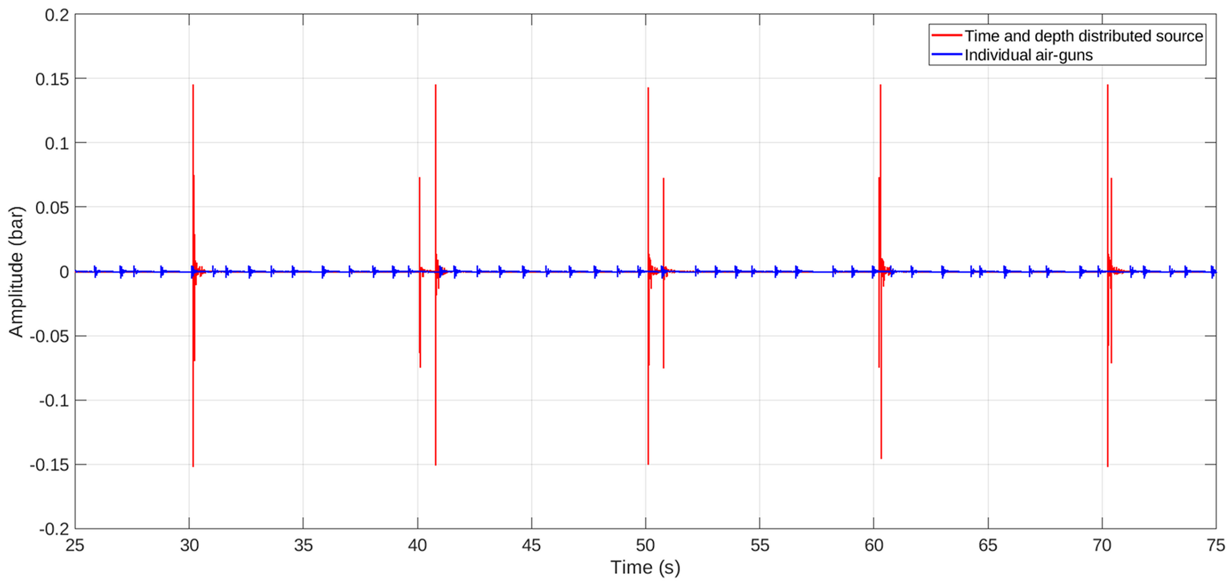


**Figure 8** Comparison of sound pressure levels at a distance of 750 m from a time and depth distributed source consisting of 66 air-guns in total triggered with a mean interval of 10 seconds (red curve), and when triggering 12 individual air-guns each with a mean interval of 12 seconds corresponding to 12 triggerings per 12 seconds (blue curve).

By deploying strings of air-guns in different cross-line positions emitting a wavefield that is spatially white in this direction, it is possible to output as many common receiver gathers as there are strings with air-guns, or it is possible to combine wavefields from multiple arrays in any combination to obtain desired source arrays. The example data shown in Fig. 5 were acquired with continuous recording, emitting continuous source wavefields from six strings with air-guns and with the configuration shown in Fig. 6. When triggering individual air-guns with very short time intervals emitting a continuous source wavefield, the continuously recorded seismic data contains signals that are interfering with each other all the time, as shown in Fig. 5. Because of the whiteness of the spectrum in the cross-line direction, it is possible to extract the

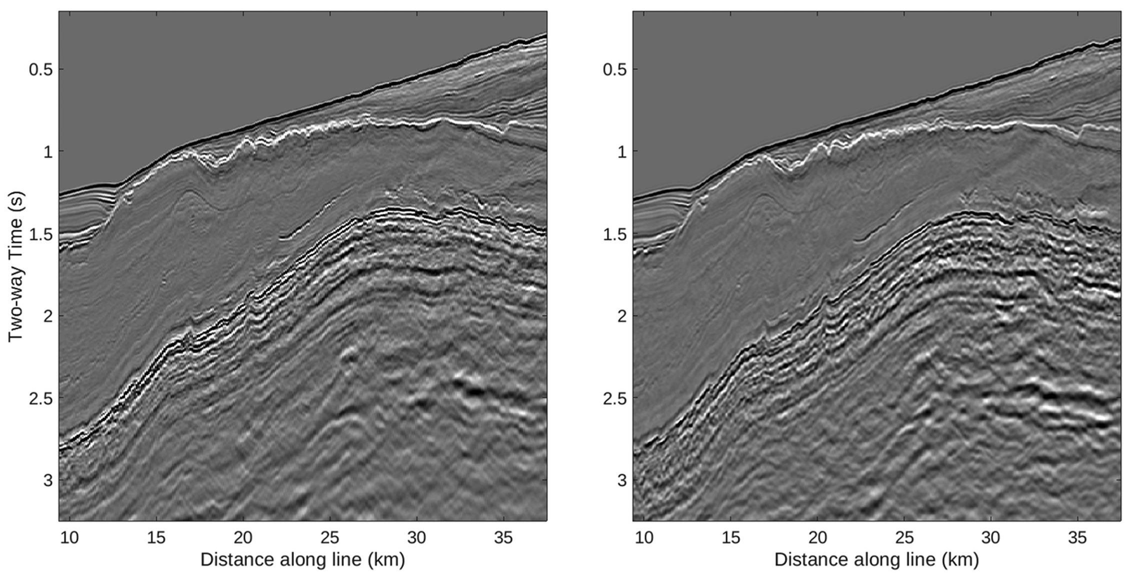


**Figure 9** Final migrated stack of data acquired with a time and depth distributed source (left), and of data acquired by triggering individual air-guns with a mean interval of 1 second (right).

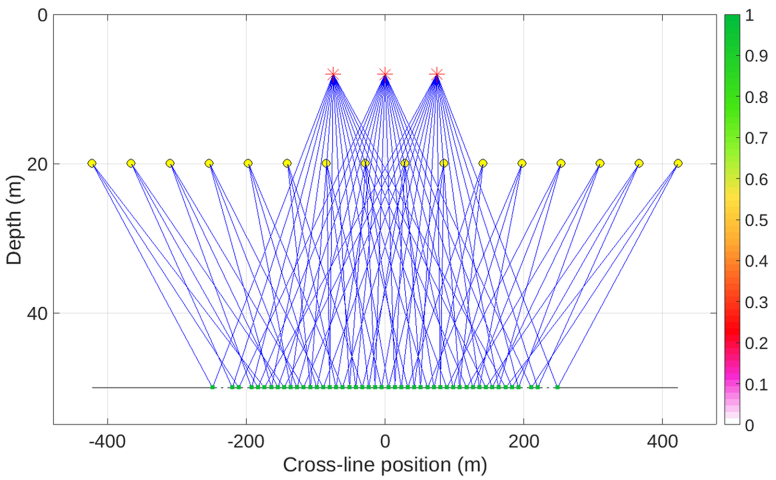


**Figure 10** Towed streamer configuration with three sources, 75 m separation, and 16 streamers, 56.25 m separation. The nominal sail line spacing with this configuration is 450 m. The coloured squares at the reflector level shows the number of hits per bin in the cross-line direction.

response of the earth associated with each of the six strings as illustrated in Fig. 7. This means that six point sources can be in the output from the source deconvolution effectively representing a six-source configuration. This ability combined with the near continuous wavefield emitted from each source means that the spatial sampling can be improved both in-line as well as cross-line compared to conventional methods.

## DATA EXAMPLES

An ≈60 km two-dimensional (2D) line south-east of the Faroe Island has been acquired in order to illustrate how the seismic method utilizing continuous source and receiver wavefields compares to other methods. The line was acquired with a 6 km dual-sensor streamer, the seismic data were recorded continuously, and the source consisted of six strings with two 150 cubic-inch air-guns on each string. These 12 air-guns were triggered individually with a mean interval of 1 second, i.e. it took about 12 seconds until the same air-gun was triggered again. The strings of air-guns were deployed at 6 m, 10 m and 14 m depth resulting in complementary bubble periods and ghost functions. The 2D line was acquired in a position where a line had been acquired previously with a time and depth distributed source (Parkes and Hegna 2011). That source consisted of 66 air-guns in two sub-sources: one 4800 cubic-inch sub-source at 14 m depth and one 2400 cubic-inch sub-source at 10 m depth. The shot spacing in this data set was 25 m. Significantly less energy was emitted from the source generating a continuous wavefield compared to the time and depth distributed source. The difference in emitted pressure

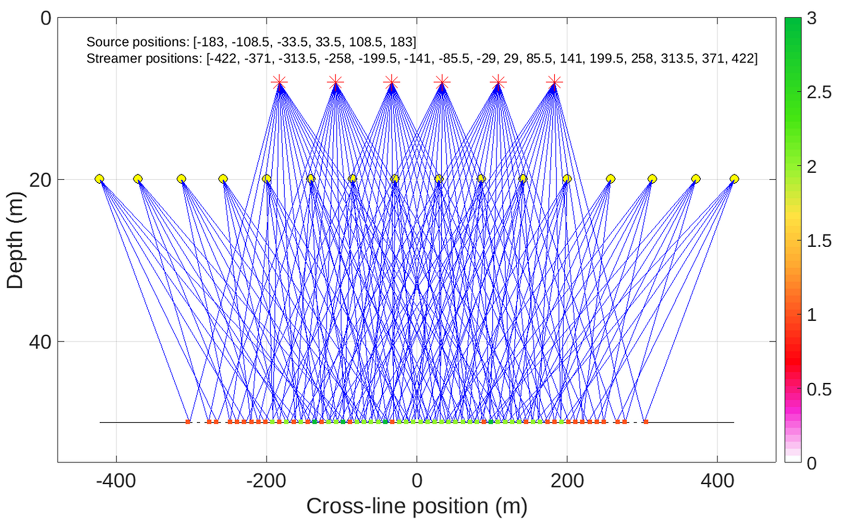


**Figure 11** A 6-source, 16 streamer, configuration determined through an optimization process. The source and streamer positions are listed in the upper part of the image.

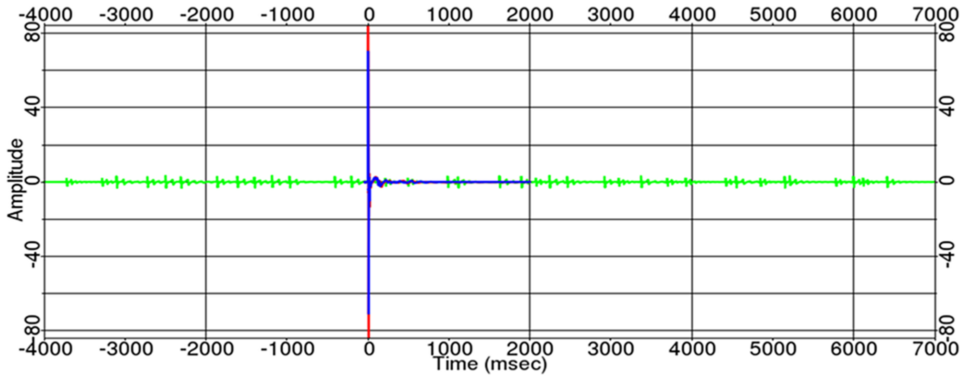


**Figure 12** Amplitude (bar-m) as a function of time for a 4130 cubic-inch source array (red curve), 3090 cubic-inch source array (blue curve) and when triggering one air-gun at a time in a near-continuous fashion (green curve).

levels is illustrated in Fig. 8, clearly demonstrating the environmental benefit in form of reduced sound pressure levels gained by spreading the source energy out in time. The main challenge in the area where these 2D lines have been acquired is penetration through basalt layer(s). Therefore, traditionally very powerful sources have been used to try to improve the seismic images below the basalt layer(s). The data acquired by triggering individual air-guns with a mean interval of 1 second is a very different approach, as can be seen in Fig. 8.

After the pre-processing steps consisting of correcting for the sensor responses and analogue filtering effects, noise attenuation, receiver motion correction, wavefield separation on the receiver side and finally the deconvolution of the source wavefield, the data are processed further using conventional methods. The final migrated stack of the 2D line is shown in Fig. 9 together with a migrated stack of the line acquired with a time and depth distributed source.

Despite the fact that the two data sets shown in Fig. 9 were acquired in completely different ways with significant

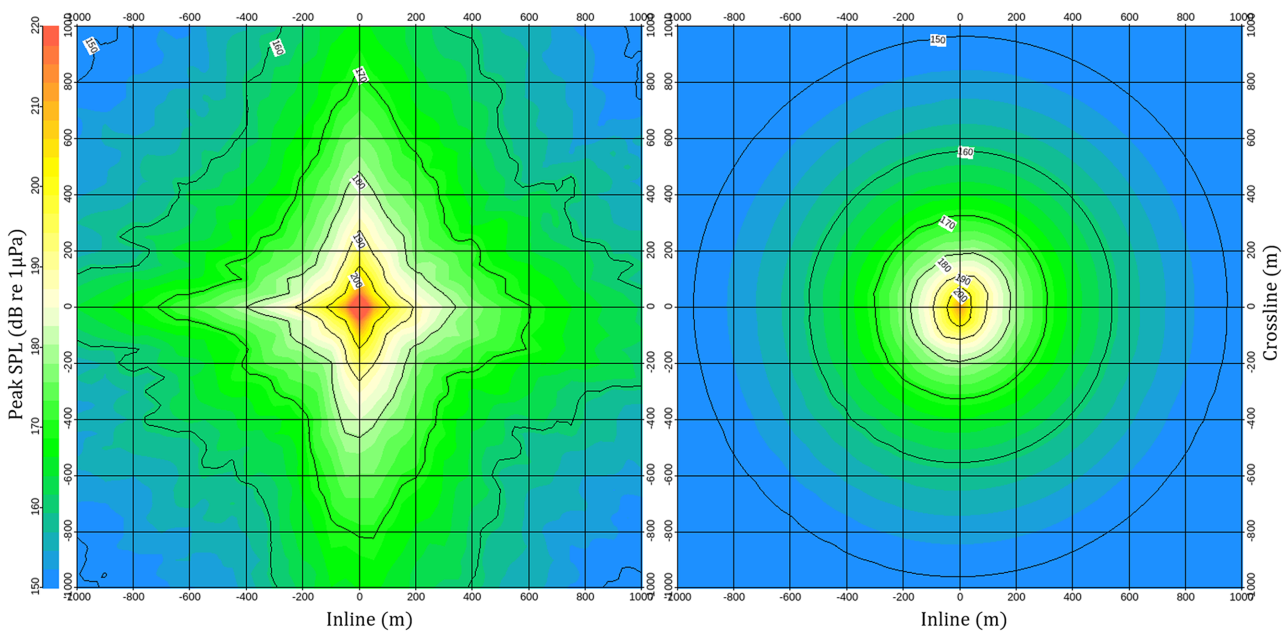


**Figure 13** Peak sound pressure levels (in dB re 1 $\mu$Pa) as a function of inline and cross-line distances in metres from the geometrical center of the source at a depth of 10 m (4 m below the source depth) for a conventional 4130 cubic-inch array (left) and when triggering individual air-guns in a near-continuous fashion (right).

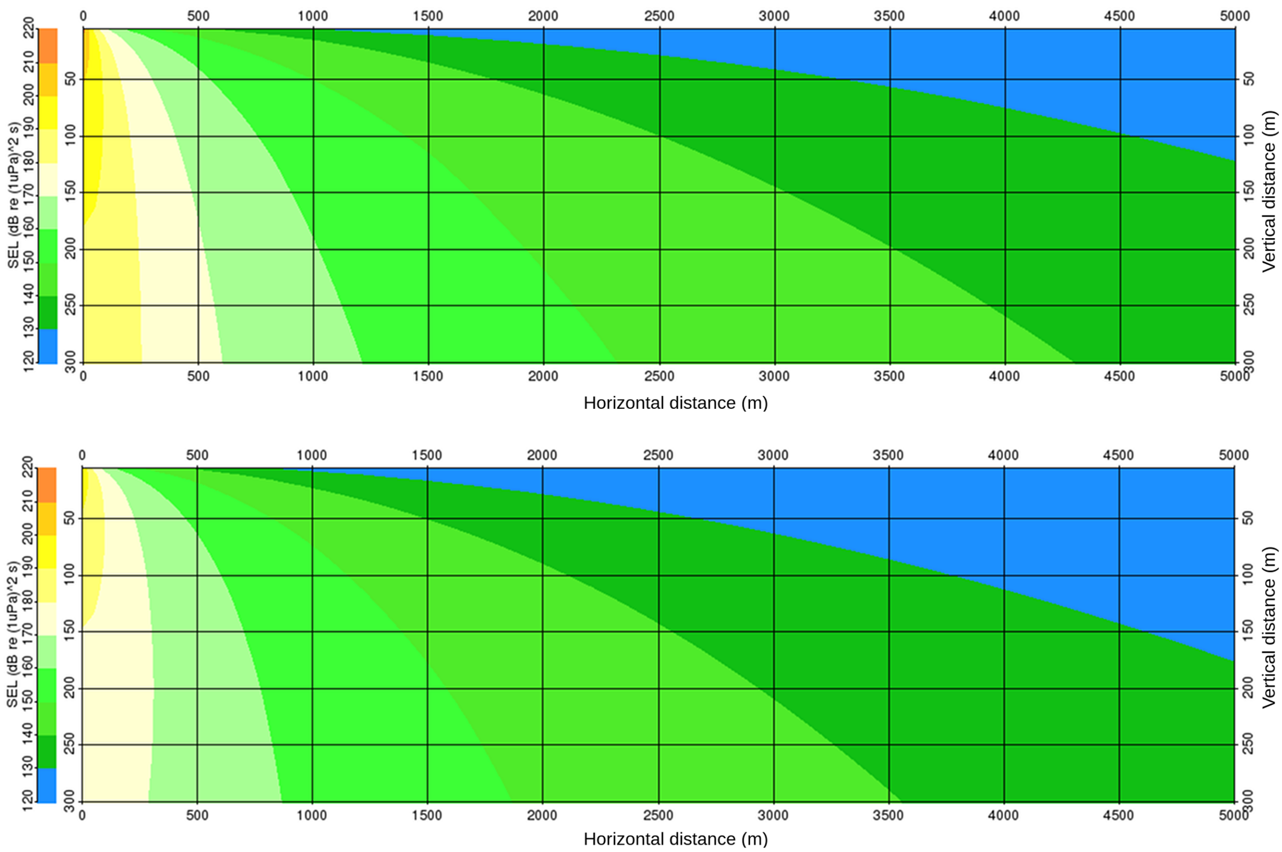


**Figure 14** Sound exposure levels (in dB re 1 $\mu$Pa$^2$s) as a function of distance from the source. Horizontal axis is in metres from the geometrical centre of the array directly aft from the vessel, while the vertical axis is depth from the sea surface in meters. The integration time is set to 10 seconds starting from the first arrival at each location. Conventional 4130 cubic-inch array (top) is compared with triggering individual air-guns in a near-continuous fashion on the bottom.

differences in the wavefields emitted from the sources, the resulting final images are fairly similar. Also the penetration below the strong top basalt reflector appearing at ≈2.75 seconds on the left-hand side and at ≈1.5 seconds on the right hand side appears to be comparable between the two methods.

## POTENTIAL IMPACT ON SURVEY EFFICIENCY

As described above and shown in Fig. 7, the methodology has been designed to be able to output one common receiver gather per string of air-guns, or alternatively output a combination of strings as arrays. If generating one common receiver gather per string of air-guns, so effectively one source per string of air-guns, the cross-line separation between the strings can be anything from dense to a wide spread of sources. If towing the strings close together, the cross-line sampling of Common Mid Point (CMP) positions can potentially be improved compared to conventional marine seismic surveys, whereas if towing the strings far apart the survey efficiency can potentially be significantly improved as well as the near-offset coverage. At present this is a concept and has not been tested.

Historically since the beginning of three-dimensional marine seismic data acquisition, the number of streamers that are towed behind the seismic vessels and the width of the streamer spreads have increased significantly. The number of sources and the width of the source spread have however remained narrow. There are several disadvantages with wide streamer spreads and narrow source spreads. Adjacent sail lines need to be overlapping in terms of receiver coverage in order to achieve uniform CMP coverage. The overlap is typically ≈50%. Another disadvantage with regards to using a narrow source spread compared to streamer spread is that the cross-line offsets (distances between the sources and the

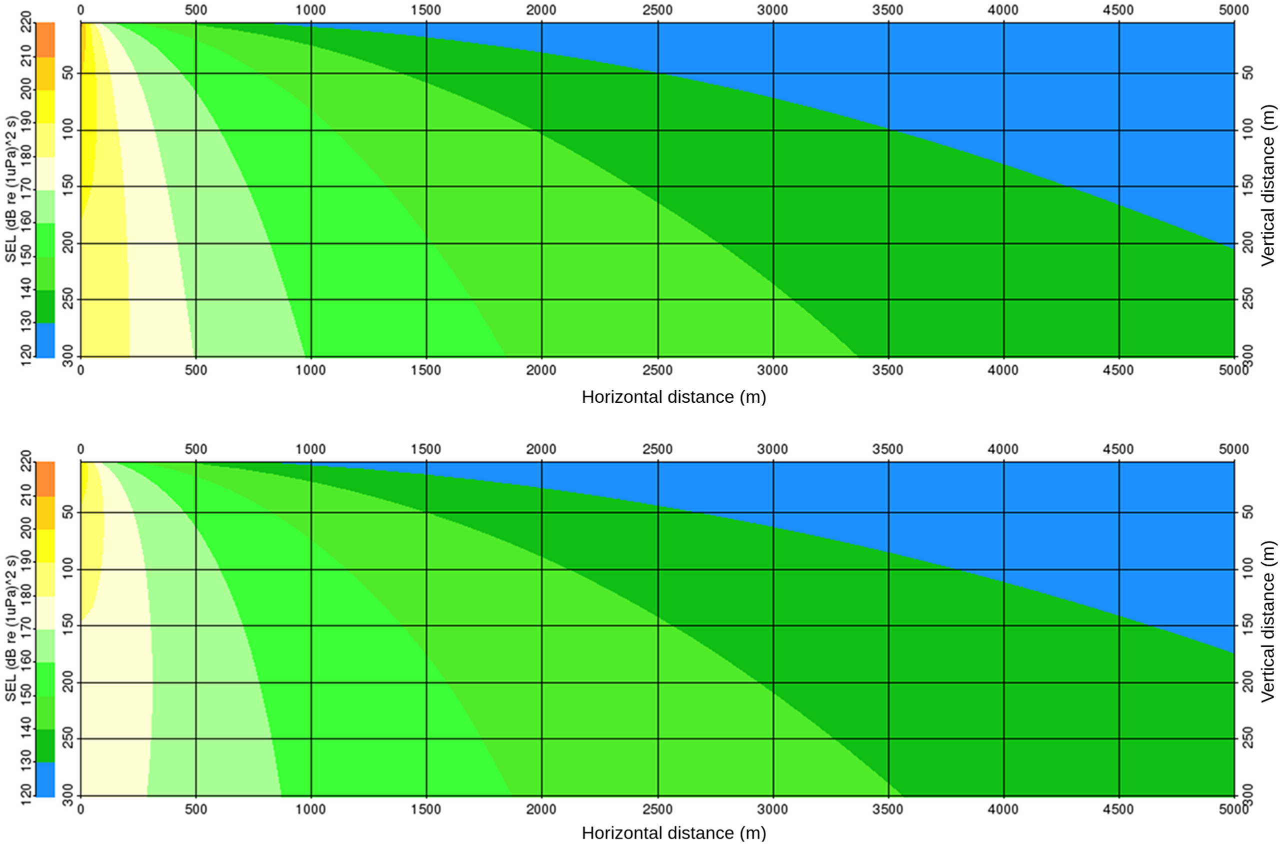


**Figure 15** Sound exposure levels as a function of distance from the source for a conventional 4130 cubic-inch array (top) and when triggering individual air-guns in a near-continuous fashion on the bottom. Direction 45° azimuth towards starboard.

receivers) are large for the outer streamers compared to the inner streamers resulting in poor near-offset coverage across the streamer spread as illustrated in Fig. 10.

To improve the acquisition efficiency as well as the near-offset coverage it would be beneficial to increase the source spread width. However, if deploying a large streamer spread with regular streamer spacing and a wide source spread with several sources and regular source spacing, the resulting coverage is not ideal. The spacing between CMP lines becomes large, the fold coverage becomes largest in the centre of the spread and the cross-line offset distribution varies from bin to bin. Therefore, it is not necessarily optimal to tow the sources and the streamers with a regular spacing. More optimum source and streamer cross-line positions can be found through an optimization process using an objective function that tries to find the source and streamer cross-line positions that minimizes the variation in CMP coverage across the entire spread and at the same time maximizes the effective sail line spacing. An example configuration determined through such a process is shown in Fig. 11. The total spread width and the number of streamers shown in Fig. 11 is similar to the streamer configuration shown in Fig. 10. However, the cross-line spacing between the streamers and the sources in Fig. 11 is not regular.

With the optimized 6-source wide tow configuration shown in Fig. 11, the nominal sail line spacing is 550 m giving a 22.2% improvement in acquisition efficiency. Also the near offset coverage is improved compared to a more traditional configuration shown in Fig. 10. This can be achieved without penalty on cross-line CMP bin size.

## POTENTIAL IMPACT ON THE ENVIRONMENTAL FOOTPRINT

There are several metrics for measuring the environmental impact of marine seismic sources (ISO 18405, 2017). The metrics that are most commonly used are peak sound pressure levels (noted peak $L_p$), and the integrated pressure over time, also

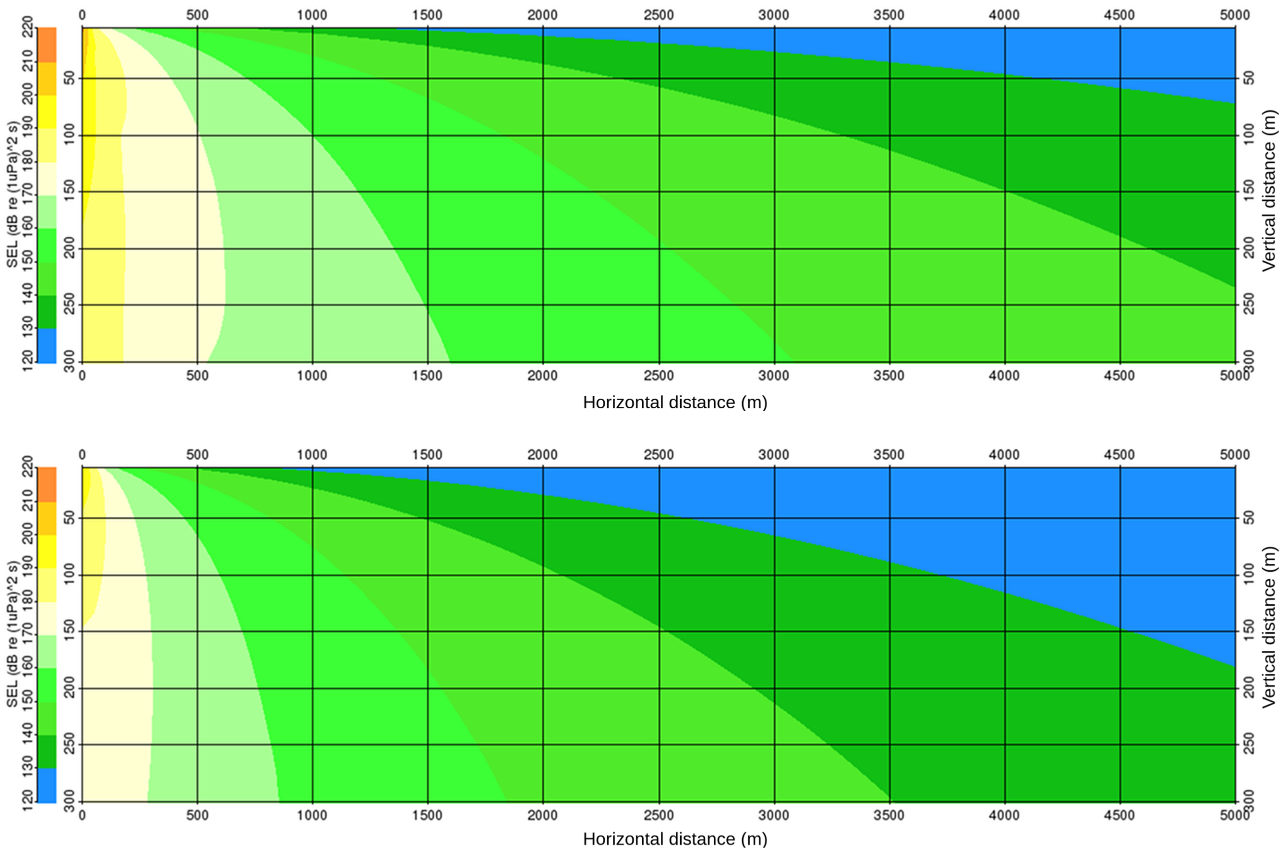


**Figure 16** Sound exposure levels as a function of distance from the source for a conventional 4130 cubic-inch array (top) and when triggering individual air-guns in a near-continuous fashion on the bottom. Direction directly cross-line starboard direction.

called sound exposure level (noted $L_{E,p}$). The sound pressure level ($L_p$) can be expressed as

$$L_p = 10\log_{10}\left(\frac{p(t)^2}{{p_0}^2}\right) dB, \qquad (4)$$

where $p(t)$ is the sound pressure as function of time $t$ and $p_0$ is the reference sound pressure equal to 1 $\mu$Pa. The peak sound pressure level is the maximum $L_p$ over the total duration of the emitted sound. The sound exposure level ($L_{E,p}$) can be expressed as

$$L_{E,p} = 10\log_{10}\left(\frac{E_p}{E_{p,0}}\right) dB = 10\log_{10}\left(\frac{\int_{t_1}^{t_2} p^2(t)\,dt}{E_{p,0}}\right) dB, \quad (5)$$

for a given time interval $[t_1, t_2]$, where $p(t)$ is the sound pressure as function of time $t$ and $E_{p,0}$ is the reference value for the sound exposure level equal to 1 $\mu Pa^2 s$. These metrics are well established in the seismic industry and are frequently used in regulatory assessments of the environmental impact of a seismic source (Southall *et al.* 2007; NOAA 2016). We will use the terms peak sound pressure level (peak SPL) and sound exposure level (SEL) below.

One of the main benefits of spreading the emitted wavefield from the seismic sources out in time is a potential reduction of peak SPL and SEL. Traditionally, in the order of 30–35 air-guns in a source array are triggered simultaneously. Figure 12 illustrates the differences in the emitted pressure levels as a function of time between a 4130 cubic-inch source array and 3090 cubic-inch array, and triggering one air-gun at a time with short randomized intervals in a near-continuous fashion.

The peak SPL in the inline and crossline directions for a conventional source (4130 cubic-inch array) and when triggering individual air-guns in a near-continuous fashion are illustrated in Fig. 13. It is clear that the peak SPL is significantly lower for all directions when triggering individual airguns. At a distance of 500 m from the geometrical centre of the source, the peak SPL when triggering individual air-guns is 12 dB below the conventional source in the inline direction, 5.4 dB below at 45° azimuth angle and 17.5 dB below in the cross-line direction.

The SEL assessment is often considered not only in the close vicinity of the array, but also for long range propagation. For an accurate assessment of long range propagation, the geology and sound speed profiles in the water column should be taken into account, and there are a number of different modelling techniques that could be considered (Etter 2009). This type of modelling approach is however depending on survey location and conditions at the time of the survey, hence a more universal approach has been used here. Both the peak SPL and SEL are here determined through modelling assuming wave propagation through a homogeneous medium with properties of water and a sea surface reflection coefficient of –1. This modelling approach is widely used in permitting processes and follows the common practice in the industry today (Goertz *et al.* 2013). Still, it is important to note that the SEL results presented here should be considered as a relative comparison and not an absolute measure. The SEL comparison of the standard array and the triggering of individual air-guns are shown for three different directions from the source in Figs 14–16. The SEL is in general lower when triggering individual air-guns compared to a conventional array.

## CONCLUSIONS

A marine seismic method has been described that treats the wavefields on both the source and the receiver side as continuous wavefields. The method requires continuous seismic data recording. Because the source wavefield is also treated as a continuous wavefield, the source can emit signals continuously while moving. An ideal continuous source wavefield should be as white as possible both in a temporal and a spatial sense to avoid deep notches in the spectrum enabling a stable multi-dimensional deconvolution. White noise has such properties. However, equipment that can generate white noise does not exist. In order to approach the properties of white noise using existing equipment, individual air-guns can be triggered with short randomized time intervals in a near-continuous fashion, generating a continuous source wavefield.

The main benefits of the proposed method are to reduce the environmental impact of marine seismic sources and to improve acquisition efficiency. Since the method is based on continuous seismic recording and the air-guns are triggered with short randomized intervals based on time with no required listening time, there are less vessel speed limitations compared to conventional methods. Also, because the source wavefield is spread out in time, the wavefields emitted from source elements in different cross-line positions can be designed such that the total emitted wavefield is spatially white in this direction. This means that source elements in multiple cross-line positions can be operated simultaneously, potentially improving the spatial sampling cross-line and/or the acquisition efficiency. The near-continuous source wavefield enables the generation of receiver gathers with denser trace spacing than in conventional methods, and this trace spacing is a processing parameter.

The peak sound pressure level is significantly reduced in all directions by triggering one air-gun at a time, compared to conventional marine seismic sources. Also sound exposure level (SEL) is reduced in most directions when triggering individual air-guns compared to conventional sources. Directly aft of the vessel SEL is lower when triggering individual air-guns. At a 45° azimuthal direction, SEL is overall fairly equal between conventional sources and triggering individual air-guns. In the crossline direction, SEL is significantly lower when triggering individual air-guns.

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## REFERENCES

Abma R., and Ross A. 2013. Popcorn shooting: sparse inversion and the distribution of airgun array energy over time. 83rd Annual International meeting SEG, Expanded Abstracts, 31–35.

Beasley C.J., Chambers R.E. and Jiang Z. 1998. A new look at simultaneous sources. 68th Annual International meeting SEG, Expanded Abstracts, 133–135.

Berkhout A.J. 2008. Changing the mindset in seismic data acquisition. *The Leading Edge*, **27**, 924–938.

Carlson D., Long A., Söllner W., Tabti H., Tenghamn R. and Lunde N. 2007. Increased resolution and penetration from a towed dual sensor streamer. *First Break*, **25**, 71–77.

Etter P.C., 2009. Review of ocean-acoustic models. *Oceans*, 2009–2014.

Frømyr E., Cambois G., Loyd R. and Kinkead J. 2008. Flam – A simultaneous source wide azimuth test. 78th Annual International meeting SEG, Expanded Abstracts, 2821–2824.

Goertz A., Wisløff J.F., Drossaert F. and Ali J. 2013. Environmental source modelling to mitigate impact on marine life. *First Break* **31**, 59–64.

ISO18405, ISO 18405:2017(E), Underwater acoustics – Terminology. International Organization for Standardization, https://www.iso.org/standard/62406.html.

Mueller M.B., Halliday D.F., van Manen D.-J. and Robertsson J.O.A. 2016. Optimizing near-orthogonal air-gun firing sequences for marine simultaneous source separation. *Geophysics* **81**, 415–423.

Mueller M.B., Robertsson J.O.A. and Halliday D.F. 2014. Simultaneous source separation using encoded source sequences. 76th Conference and Exhibition EAGE, Extended Abstracts, Th ELI2 03.

NOAA 2016. Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing underwater acoustic thresholds for onset of permanent and temporary threshold shifts. *NOAA Technical Memorandum*, NMFS-OPR-55.

Parkes G. and Hegna S. 2011. An acquisition system that extracts the earth response from seismic data. *First Break* **29**, 81–87.

Pramik B., Bell M.L., Grier A. and Lindsey A. 2015. Field testing the AquaVib: an alternative marine seismic source. 85th Annual International meeting SEG, Expanded Abstracts, 181–185.

Robertsson J.O.A., Amundsen L. and Sjøen Pedersen Å. 2016. Wavefield signal apparition, Part I – Theory. 78th Conference and Exhibition EAGE, Extended Abstracts, We LHR2 05.

Robertsson J.O.A., Halliday D.F., van Manen D.J., Vasconcelos I., Laws R.M., Őzdemir K., *et al*. 2012. Full-wavefield, towed-marine seismic acquisition and applications, 74th Conference and Exhibition EAGE, Extended Abstracts, Z015.

Sjøen Pedersen Å., Amundsen L. and Robertsson J.O.A. 2016. Wavefield Signal Apparition, Part II – Application to simultaneous sources and their separation. 78th Conference and Exhibition EAGE, Extended Abstracts, We LHR2 06.

Southall B.L., Bowles A.E., Ellison W.T., Finneran J.J., Gentry R.L., Greene Jr. C.R., *et al*. 2007. Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals* **33**, 411–522.

Ziolkowski A. 1984. The Delft airgun experiment. *First Break* **2**, 9–18.