The continuous wavefields method - using electro-mechanical sources

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Summary

In this paper we describe how the methodology utilizing continuous wavefields on both the source and the receiver side may be used with different source concepts emitting different types of signals. The background theory will be discussed before methodology is demonstrated on synthetic data that have been simulated for potential types of signals emitted by electro-mechanical sources.

Introduction

A methodology that can utilize the benefits of continuous wavefields on both the source and the receiver side has been developed and demonstrated on synthetic and real data acquired with air-guns that are actuated with short randomized time intervals (Hegna et al., 2018a; Klüver et al., 2018). In this paper we describe how the continuous wavefields method performs with different source wavefields, and what the limitations are depending on the characteristics of the emitted source wavefield.

For our method, the ideal continuous signals emitted from a source are band-limited white noise; however, the method can be used with any type of source wavefield. The temporal and spatial resolution of the extracted earth response must be kept within the limits of the source and receiver wavefields.

The characteristics of the emitted wavefield may be very different between different types of devices, e.g. air-guns compared to marine vibrators. In this paper, the theory behind the extraction of the earth responses with different source wavefields will be explained, and the method will be demonstrated on synthetic data with signals that may be emitted with electro-mechanical sources.

Theory

With continuous recording on the receiver side, pre-conditioning steps such as correction for sensor responses and noise attenuation is done on the continuous records. After these pre-conditioning steps, the received signals need to be assigned to the locations along the line trajectory where they were received. In addition, with multicomponent sensors the received wavefield is separated into up- and down-going components (Carlson et al., 2007). These steps can be expressed by the following single equation:

$$P_{up}(\omega, k_{xr}) = \frac{1}{2}\sum_{x_r}\sum_{t}[p_{tot}(t, x_r) - \frac{\rho\omega}{k_{zr}}v_{ztot}(t, x_r)]e^{-i(\omega t + k_{xr}x_r)}$$

(1)

where P_{up} is the up-going pressure field, ω is the angular frequency, k_{xr} is the horizontal wavenumber along the receiver axis, p_{tot} is the measured total pressure field in lateral position x_r along the line trajectory at time t, ρ is the density in water, k_{zr} is vertical wavenumber, and v_{ztot} is the measured total vertical particle velocity field. The horizontal wavenumber along the receiver axis needs to be defined such that it covers the entire sail line along the trajectories traversed by the receivers. The maximum horizontal wavenumber (i.e. the Nyquist wavenumber) is defined by the spacing between the receivers / receiver arrays along the streamers. The maximum lateral resolution on the receiver side is therefore limited by the receiver spacing. The maximum temporal resolution is limited by the temporal sampling rate and the sensor responses. In addition, in order to achieve a correct result after motion correction and wavefield separation, the temporal resolution is limited by the spatial sampling of the receivers.
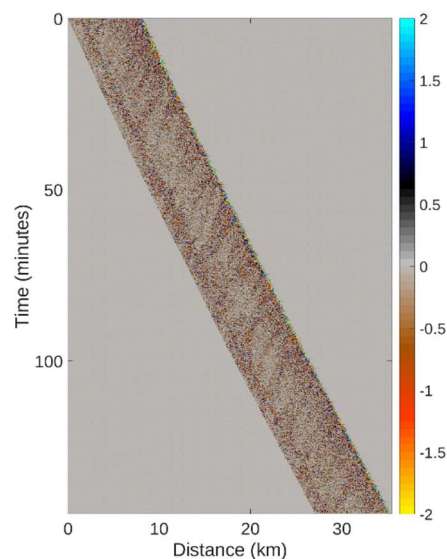

Figure 1: A typical continuous receiver wavefield after motion correction and wavefield separation.

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The emitted source wavefield needs to be known to deconvolve it from the received wavefield. The source deconvolution process to extract the response of the earth has been described in Hegna et al. (2018b). The emitted source wavefield can be expressed by the following equation:

$$S_{tot}(\omega, k_{xs}) = \sum_{x_{sn}} \sum_{t} s_n(t, x_{sn})[e^{-ik_{zs}z_{sn}} - e^{ik_{zs}z_{sn}}]e^{-i(\omega t + k_{xs}x_{sn})}$$

$$(2)$$

where S_{tot} is the total emitted wavefield, ω is the angular frequency, k_{xs} is the horizontal wavenumber along the source axis, s_n is the signal emitted by one source element in position x_{sn} along the line trajectory at time t, k_{zs} is the vertical wavenumber, and z_{sn} is the depth of the source element at time t and in lateral position x_{sn} along the line trajectory. If the source consists of multiple source elements, the contributions from all elements need to be summed into the total source wavefield.

As can be seen from equations (1) and (2), there is a clear symmetry between the source and the receiver side. One difference is that in the case of multicomponent streamers, no assumptions have to be made with regards to the sea surface and hence the ghost function. On the source side however, a flat sea surface and a reflection coefficient of -1 is assumed in equation (2).

When determining the source wavefield to be deconvolved from a received wavefield in a given receiver location, the horizontal wavenumber along the source axis needs to be defined such that it covers all positions in a sail line that can contribute to the receiver location where source signals have been emitted. The maximum horizontal wavenumber (the spatial resolution of the common receiver gathers) is defined by the spacing between the positions where signals have been emitted. If the source element(s) emit signals continuously while moving, e.g. band-limited white noise, it is possible to choose the maximum horizontal wavenumber in processing. In other words, the locations of the band-limited point sources output from the source deconvolution step can be anywhere along the source line trajectory. If the source(s) emit signals in particular discrete positions along the line, the spacing between the band-limited point sources output from the source deconvolution step is limited by the spacing between the positions where sources emit signals. The temporal resolution of the receiver gathers is limited by the temporal resolution on the receiver side and the bandwidth of the signals emitted by the sources. In addition, the temporal resolution is limited by the spatial sampling of the receiver gathers that it is possible to solve for.
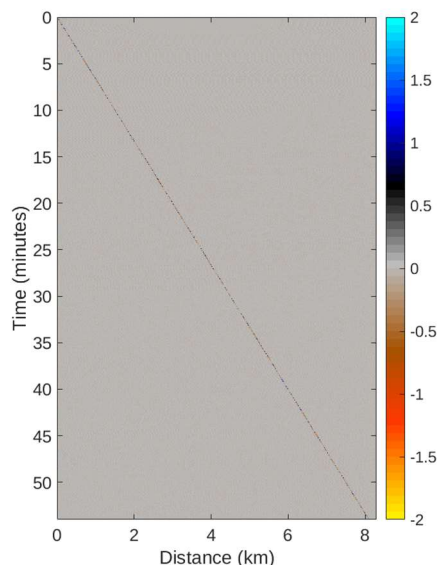

Figure 2: A source wavefield from a source that is continuously emitting band-limited white noise while moving along a line trajectory.

This means that the temporal and spatial resolution of the earth responses in the final common receiver gathers will depend upon the characteristics of the emitted source wavefield and on the receiver system.

If the source is towed behind a vessel and it consists of air-guns, air-bubbles are left behind as the source is moving away from the locations where air-guns were actuated. In addition, the air-bubbles are rising in the water column as a function of time after the air was released into the water. This means that the lateral position of the signals emitted by one actuation (a point source) is essentially stationary, and the depth of the point source is decreasing as a function of time. If a source element is towed behind a vessel and it emits signals continuously while moving, e.g. a marine vibrator, then the lateral position of the point source is constantly moving, and the depth only varies if the depth of the source element is changing e.g. due to sea surface waves. However, as long as the actual emitted signals and the (x,y,z) positions as a function of time are known and used as input into equation (2), the earth response is recovered when deconvolving the emitted source wavefield from the received wavefield, irrespective of source type. Therefore, the continuous wavefields method can be used with any type of source and any combination of different source types.

The continuous wavefields method has already been demonstrated on synthetic and real data where individual air-guns are actuated with short randomized time intervals

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approaching the properties of band-limited white noise (Hegna et al., 2018a; Klüver et al., 2018). The application of the continuous wavefields method with electro-mechanical sources, e.g. marine vibrators, will be shown below. Three different types of signals that potentially may be generated with electro-mechanical sources have been considered: linear sweeps, Gold sequences (Dixon, 1994), and random noise with a band-limited amplitude spectrum.

Linear Sweeps

Linear sweeps have been commonly used with vibrator type sources. It is well known from land acquisition that the signal to noise ratio in the resulting seismic images can be improved by extending the temporal length of the sweeps. This is the case when the source is stationary while sweeping. When the source is towed behind a seismic vessel in motion the situation is different. If the sweep length and the time interval between consecutive sweeps are too long, spatial aliasing towards higher frequencies may become an issue due to the spacing between each time a certain frequency is emitted. To mitigate some of these issues, the time interval between the end of one sweep and the start of the next sweep may be randomized. In this synthetic simulation a randomized time interval between 4 and 6 seconds has been simulated. The linear sweeps are 5 seconds long and cover a frequency range from 10 to 100 Hz, tapered down at both ends of this frequency range, and the phase at the start of each sweep is randomized. The first three sweeps are shown in Figure 3.

Gold Sequences

Gold sequences (Dixon, 1994) are a type of binary sequence used in telecommunication and satellite navigation. The Gold sequences are made orthogonal from sequence to sequence. Unlike linear sweeps, with Gold sequences a broad frequency range is emitted all the time during a sequence. The temporal length of the Gold sequences used here is 5 seconds, and they cover a similar frequency band as the linear sweeps. In this simulation there is no time
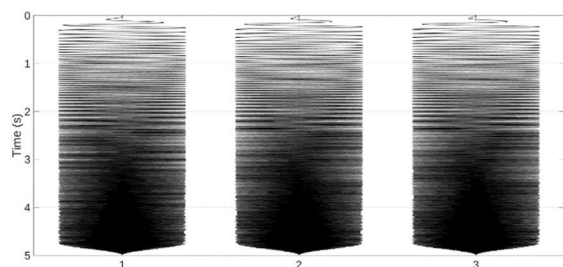
interval between consecutive sequences. Therefore, a continuous signal has been simulated. The first three Gold sequences that have been concatenated are shown in Figure 4.
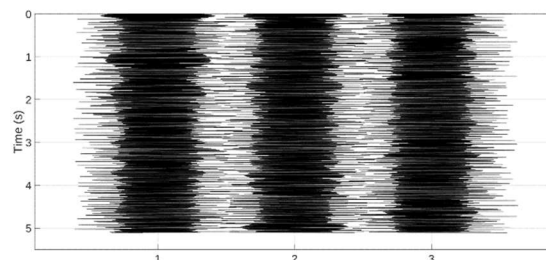

Figure 4: The first three 5 s Gold sequences that have been concatenated into a continuous signal.

Random Noise

The third type of signal that has been simulated is band-limited random noise. The amplitude spectrum of a Gold sequence is used to generate the band-limited random noise. The phase spectrum is random. The random noise traces generated are 5 seconds long, and they have been concatenated in a continuous trace without any time gaps. The first three band-limited random noise traces that have been concatenated are shown in Figure 5.

Results

Synthetic traces in a stationary location have been computed based on the three different signal types described above, and based on an earth response shown in the panel on the left in Figure 6. This earth response includes both reflections and diffractions. A synthetic receiver trace in a stationary position simulated based on linear sweeps is shown on the right hand side of Figure 6. The synthetic trace has been derived based on three-dimensional propagation of the emitted wavefield into the earth model and then back to the receiver location.
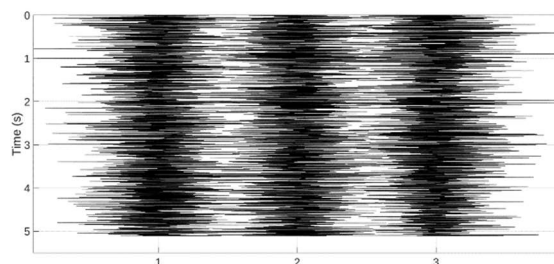

Figure 3: The first three 5 s linear sweeps that have been concatenated together with a four to six second randomized time gap between each sweep.

Figure 5: The first three 5 s random noise traces that have been concatenated into a long continuous signal.

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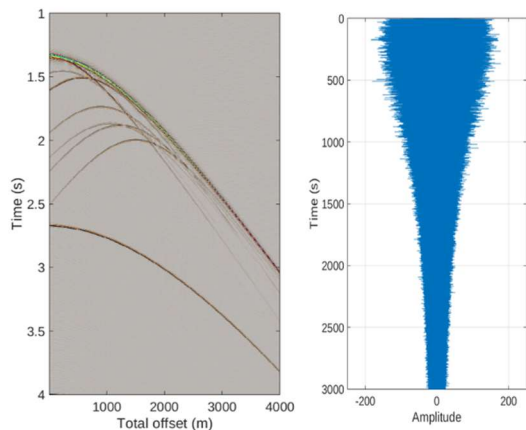
Figure 6: The earth model (left) and a synthetic trace in a simulated stationary receiver location based on linear sweeps (right).

The results after deconvolving the source wavefield based on linear sweeps from the receiver trace shown in Figure 6 is shown to the left in Figure 7. The panel to the right shows the difference between the deconvolution result and the desired output shown to the left in Figure 6. Only some minor errors can be observed related to spatial aliasing of the sweeps for the highest frequencies. Therefore, the bandwidth that has been solved for is close to the limit of what can be achieved with this type of a source wavefield.

Figures 8 and 9 show the equivalent results after deconvolving the source wavefields based on Gold sequences and band-limited random noise, respectively. These results are very comparable to the results shown with linear sweeps, with the exception that there are no errors related to spatial aliasing in contrast to observations with the linear sweeps.
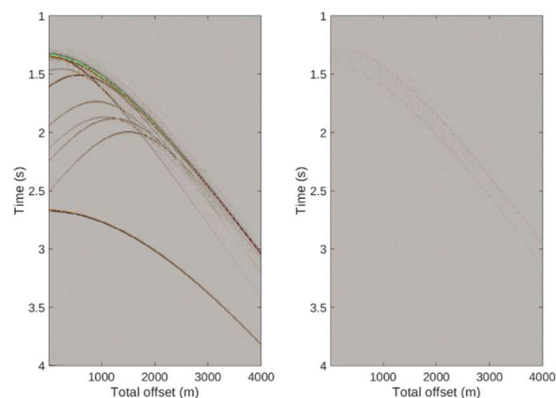

Figure 7: Deconvolution result with linear sweeps (left), and the difference to the desired result (right).
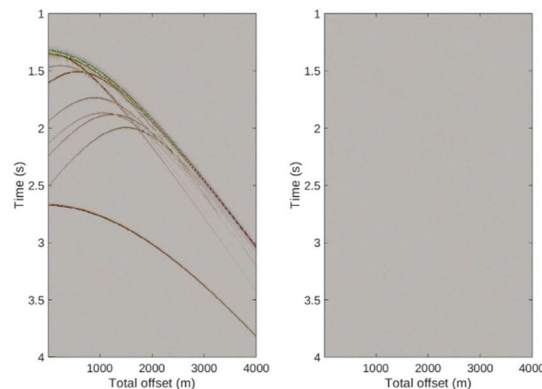

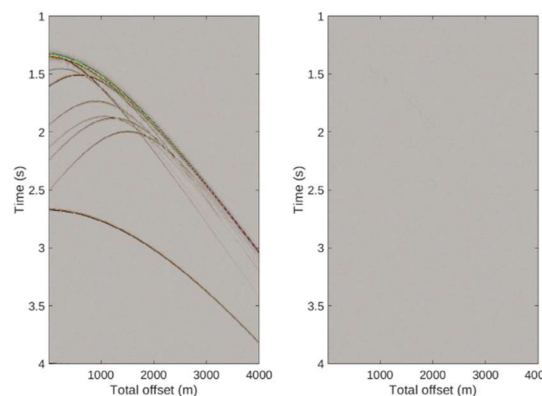*Figure 8: Deconvolution result with Gold sequences (left), and the difference to the desired result (right).*

Figure 9: Deconvolution result with random noise (left), and the difference to the desired result (right).

Conclusions

It can be concluded from simulations using different types of signals emitted from electro-mechanical sources that the continuous wavefields method may be used on such seismic data. The results after the source deconvolution are very similar even if the phase characteristics of the emitted source wavefields are very different. Care must be taken with linear sweeps, with regards to the temporal length of the sweeps, time interval between consecutive sweeps, and the desired maximum resolution in the end result, to avoid spatial aliasing at higher frequencies.

Acknowledgements

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