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Making the Transition from Discrete Shot Records to Continuous Wavefields - Methodology

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Summary

A method that extracts the response of the earth from continuous wavefields on both the source and the receiver side is presented. Seismic data recorded continuously are treated over the entire time length at once. The source(s) can emit signals continuously while moving. The entire source wavefield contributing to each stationary receiver position is derived and used to extract common receiver gathers with the response of the earth. The trace spacing in the resulting gathers can be chosen in processing and corresponding anti-aliasing protection is applied. With the proposed method, no minimum listening time is needed since both the source(s) and the receivers are operating continuously. The emitted sound pressure levels are reduced by spreading the emitted energy out in time. Multiple sources can be operated simultaneously by designing each source such that the correlation between the wavefields emitted from each of them is minimized. In a companion paper (Klüver, T., Hegna, S., and Lima J., 2018, Making the transition from discrete shot records to continuous wavefields – Real data application: Expanded abstract submitted to the EAGE annual meeting) we discuss source design using existing equipment and show application of the proposed method on real data.

Introduction

Conventional marine seismic methods are based on acquiring and processing discrete 'shot records'. This requirement imposes several limitations. One of the main limitations is that sufficient listening time is needed in order to be able to image to required depths in the subsurface. Therefore, marine source arrays have been designed to emit a wavefield that is approaching a spike. The maximum vessel speed has been limited, and the shot spacing is large compared to the receiver spacing.

In order to increase the efficiency and/or shot density compared to conventional seismic methods, various blended or simultaneous source techniques have been proposed (e.g. Beasley et al., 1998; Berkhout, 2008; Frømyr et al., 2008; Robertsson et al. 2016; Sjøen Pedersen et al., 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 like 'Popcorn shooting' (Abma and Ross, 2013), the signals are spread out in time. This means that the peak sound pressure levels emitted from the sources can be reduced, and the correlation between wavefields emitted from multiple sources operated simultaneously can also be reduced. However, these methods are still based on discrete shot records.

This paper describes a method that 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(s) can emit signals continuously while moving. The entire source wavefield contributing to each receiver position is utilized in order to extract the response of the earth. The motivation behind the method is reducing the environmental impact of marine seismic surveys, and to improve acquisition efficiency. With this method the sound pressure levels are reduced because the sound energy emitted from the sources is spread out in time, no minimum listening time is needed, the trace spacing in common receiver gathers can be much denser than in conventional methods, and multiple sources can be operated simultaneously.

Proposed method

With the advent of continuous seismic recording, data recording is no longer triggered by position. Seismic data are typically recorded continuously for as long time as it takes to acquire a sail line. After some pre-conditioning of the data, such as correction for sensor responses and noise attenuation, any motion of the receivers is corrected for as illustrated in Figure 1.

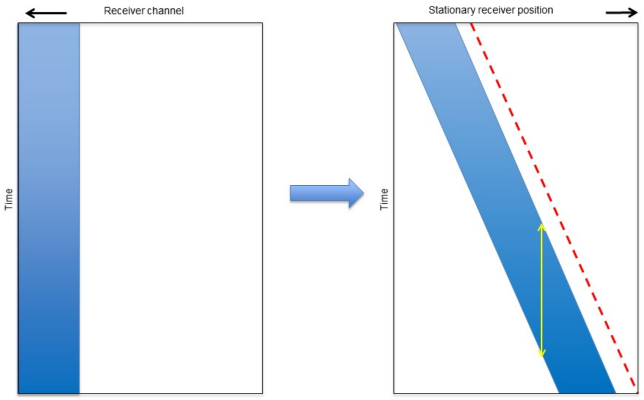

Figure 1 *The blue area to the left illustrates a seismic data record recorded continuously, with a temporal extent of a sail line, and a lateral extent corresponding to the streamer length. The blue area to the right represents the seismic data after receiver motion correction. The spatial extent of 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.*

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

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

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. If the data are recorded in stationary positions, e.g. by nodes located on the ocean bottom, the receiver motion correction is not necessary.

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 Figure 2. The time axis of the receiver trace also represents an offset axis as shown on the figure. 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 Figure 2.

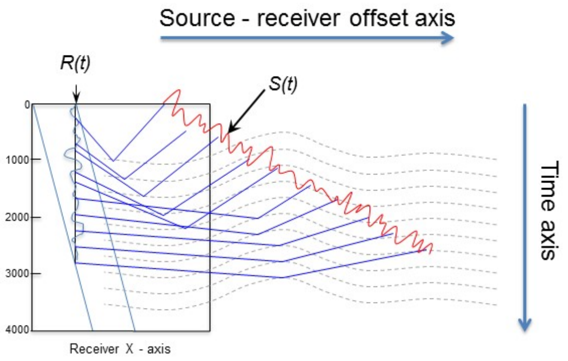

Figure 2 *R(t) is a stationary receiver trace as a function of time, and S(t) are the source signals emitted as a function of time in different offsets relative to the receiver location. The grey dashed lines represent one reflector in the sub-surface, and the blue lines represent some of the ray-paths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

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

$$R(\omega) = \sum_n E(\omega,k_n)S(\omega,k_n), \tag{2}$$

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

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

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 coherent signals associated with the response of the earth are extracted, and where all possible source emission angles are considered in each iteration.

Synthetic data examples

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 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 Figure 3.

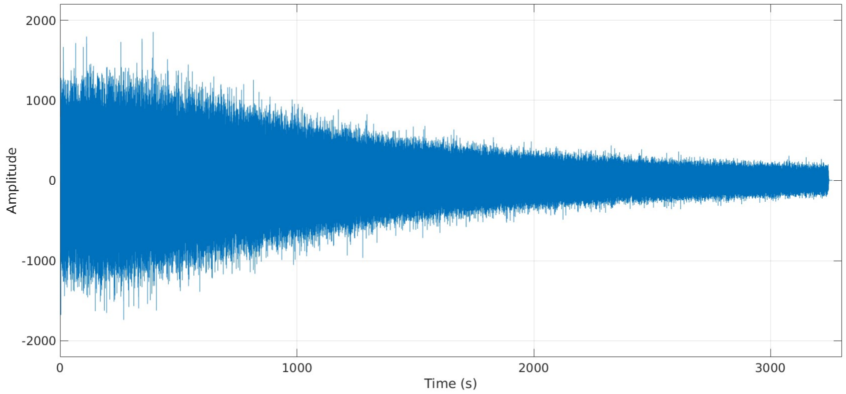

Figure 3 *Simulated receiver trace in a stationary position containing more than 3000 seconds of signals received continuously.*

The receiver trace shown in Figure 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 Figure 4.

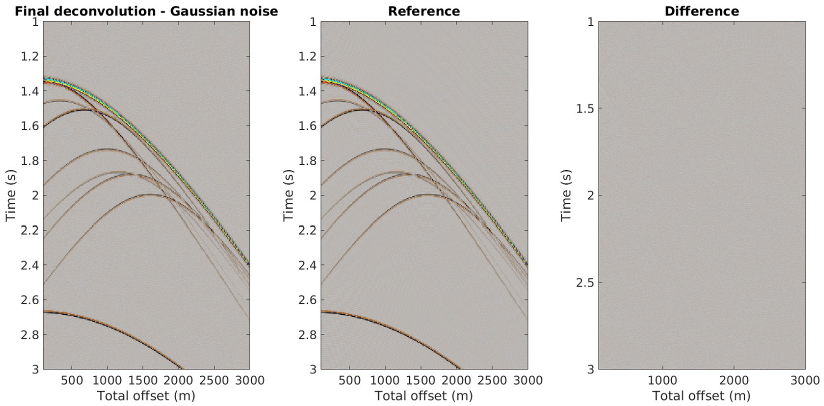

Figure 4 *Results from the iterative source deconvolution process shown to the left, using the white noise source signals and the receiver trace shown in Figure 3 as inputs. The image in the middle shows the desired output, and the image to the right shows the difference between the deconvolution result and the desired result.*

Conclusions

A method that treats the wavefields on both the source and the receiver side as continuous wavefields and that takes any continuous motion of the sources and/or receivers into account has been described. The method does not require discrete shot records, and can handle source(s) that are continuously emitting signals while moving. The main challenge with the method is that the receiver wavefield contains a superposition of all possible source emission angles. Therefore, a method that extracts the response of the earth from the source and receiver wavefields has been developed that considers all possible source emission angles, and extracts the response of the earth in an iterative process. Because the signals emitted from the sources can be spread out in time, the peak sound pressure levels can be significantly reduced compared to conventional marine seismic sources. Furthermore, the spatial sampling of the resulting common receiver gathers can be much denser than in conventional seismic data. The output common receiver gathers with a specified trace spacing are anti-alias protected. Another aspect of the method is that the maximum depth to image is not limited by a record length.

Acknowledgements

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