Doctoral Thesis

Encoding techniques for marine seismic sources & their applications

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Encoding techniques for marine seismic sources & their applications

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Abstract

Despite the continuous development of new marine seismic acquisition technology, there are still a number of factors which impair the quality of marine seismic data, such as noise, illumination, bandwidth and signal aliasing. Whereas many advances have been made to resolve these limitations on the receiver-side, they have remained a challenge for the source-side. Particularly the ghost problem and the insufficient spatial sampling pose challenges to the source-side of marine seismic acquisition and require innovative solutions. This thesis addresses those source-side challenges by introducing encoding techniques for marine seismic sources. Whereas in conventional marine seismic acquisition the individual source-elements of marine seismic sources are activated at once to generate a sharp source pulse, we encode the sources by allowing the individual source-elements to fire independently over a short period of time yielding firing sequences of individual source pulses.

The thesis starts with the demonstration of the benefits of encoding for simultaneous source separation. Simultaneous source acquisition techniques, which record the interfering signal from multiple sources, have been developed to overcome the spatial sampling restrictions on the source-side. The overlapping signal of the simultaneous sources needs to be separated so that seismic data are obtained as if they were acquired with a single source. This separation is challenging, but we show that the orthogonality of encoding sequences, characterized by minimal crosscorrelation and optimal autocorrelation properties, can be exploited as a separation feature. Using a multifrequency implementation of a separation method, which separates the simultaneous sources based on a coherency approach, we show how the orthogonality of the encoding sequences can be exploited. In the presented examples, this method significantly outperforms conventional simultaneous source separation techniques, which are only based on the time-dithering of the simultaneous sources. The combination of multiple frequency components in the separation method also enables a better handling of realistic source spacings with respect to spatial aliasing compared to the majority of previous techniques.

Since ideal orthogonal, encoding sequences cannot be emitted by real marine seismic sources, the second part of the thesis is dedicated to finding near-orthogonal firing sequences for the encoding of real air-gun sources. For that reason, we develop
an optimization method, which constructs different encoding sequences by varying the firing times of the individual air guns and evaluates their orthogonality properties. Using a simulated annealing approach, optimized air-gun firing sequences with the desired orthogonality properties are found. The controllable crosscorrelation and autocorrelation features of these designed encoding sequences yield a consistent improvement for simultaneous source separation in comparison to the encoding with random air-gun firing sequences. The optimization method developed in this thesis also provides a tool for changing the encoding sequences of the simultaneous sources from shot to shot, making the otherwise required time-dithering of the secondary source redundant.

The application of the sequence optimization method to air-gun source elements, deployed at different depth levels, enables the encoding of the source ghost wavefield due to the different source ghost time delays. We show that firing sequences for these multi-depth air-gun sources can be designed, so that their ghost-wavefield is orthogonal to their direct, downgoing wavefield. This observation enables the consideration of the ghost-wavefield as a secondary source. The variation of the firing sequences from shot to shot allows the separation of this ghost-source with the developed simultaneous source separation method.

The marine seismic source encoding techniques developed in this thesis can be employed to acquire source-gradient data, which enable numerous benefits such as source-side deghosting and source-side reconstruction. In addition, the improvement of simultaneous source separation achieved with source encoding could enable full-wavefield vector-acoustic imaging.
Zusammenfassung


Diese Disseration zeigt zuerst die Vorteile der Kodierung seismischer Quellen zur Trennung des Signals simultaner Quellen auf. Bei der marinen Akquisition mit simultanen, seismischen Quellen wird das Wellenfeld von mehreren interferierenden, gleichzeitig aktivierten Quellen aufgezeichnet. Das Aufzeichnen von solchen überlagerten Quellen erlaubt es die Einschränkungen der räumlichen Abtastung auf der Quellenseite zu überwinden. Allerdings müssen die überlagerten Wellenfelder mit Signalverarbeitungstechniken wieder getrennt werden, um die einzelnen seismischen Signale zu erhalten, die zu den jeweiligen simultanen Quellen gehören. Diese Wellenfeldtrennung ist technisch herausfordernd, aber wir zeigen, dass die Orthogonalität kodierter Quellsequenzen, welche durch minimale Kreuzkorrelation und optimale Autokorrelations-Eigenschaften gekennzeichnet sind, zur Verbesserung der Wellenfeldtrennung verwendet werden kann. Mit Hilfe eines Multi-Frequenz-Trennverfahrens, welches die simultanen Wellenfelder basierend auf einem Kohärenz-Ansatz trennt, zeigen wir, dass die Orthogonalität der Sequenzen optimal genutzt werden kann. Diese Methode übertrifft die Wellenfeldtrennung mit herkömmlichen
Verfahren, welche allein auf der zeitlichen Verzögerung simultaner Quellen basieren, deutlich. Im Gegensatz zu anderen gebräuchlichen Trennungsalgorithmen erlaubt die Kombination mehrerer Frequenzkomponenten die Wellenfeldtrennung mit realistischen Quellenabständen.


Die in dieser Arbeit entwickelten Techniken zur Kodierung mariner seismischer Quellen ermöglichen auch die Akquisition von Quell-Gradienten. Quell-Gradienten-Daten eröffnen zahlreiche Anwendungsmöglichkeiten wie die Behebung des quellseitigen Ghost-Effekts und die quellseitige Rekonstruktion des Wellenfeldes. Darüber hinaus könnte die erzielte Verbesserung der Wellenfeldtrennung von kodierten simultanen Quellen die Akquisition des ganzen Vektor-akustischen Wellenfeldes ermöglichen.
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Chapter 1

General Introduction

Motivation

The seismic method is by far the most widely used geophysical technique for imaging the subsurface. In seismic surveying, sound waves are sent into the Earth by a seismic source. These waves then travel through the subsurface and reflect at interfaces. The reflections from these interfaces are measured by recording sensors at the surface. The measured seismic data are then processed to extract information about the subsurface and to finally obtain a visual image of the subsurface structure. Similar to doctors using ultrasonic scans or x-rays to visualize the interior of the human body, geophysicists employ the seismic method to visualize the Earth and characterize the subsurface.

Seismic imaging can be applied on various depth scales ranging from a few meters in civil engineering for site investigations to thousands of kilometers in global seismology, revealing the inner structure of the Earth. The information retrieved by mapping subsurface structures is not only of scientific importance, but also has many important direct practical applications, for instance with respect to natural hazard assessment or to find groundwater reservoirs. Seismic imaging is also a key technique in natural resource exploration. It is used to delineate and assess coal beds and mineral deposits and it is the principal tool to locate structures in the subsurface with potential oil and gas accumulations. Land and marine seismic surveys are conducted in many places on the Earth’s surface to guide the exploration, production and development of hydrocarbon reservoirs. While according to the World Energy Council (WEC) in 2013 80% of the total energy supply was based on fossil fuels, it is expected that in the year 2020 76% of the total energy supply will still be covered by fossil fuels (WEC, 2013). The BP Energy Outlook (BP, 2016) even projects that in 2035 fossil fuels will still account for almost 80% of total energy supplies. Our society depends heavily on the use of fossil fuels for: transportation, building materials, heating, pharmaceutical goods, clothing, etc. In times where worldwide hydrocarbon consumption is still increasing year after year and the discovery of new oil and gas resources becomes more and more challenging, improved seismic imaging techniques are of fundamental importance.
Since the first employment of the seismic method and its establishment as the main method for hydrocarbon exploration, the growth of the success of the oil and gas industry has closely been linked with technological advances. Particularly the development of offshore oil and gas exploration and production has been driven by significant advances in marine seismic acquisition technology. Over time the number of recording channels has steadily increased to many tens of thousands in present-day acquisition campaigns. The resulting vast data volumes can only be handled and processed with modern computational resources. In the last decades, the technological advance of marine seismic broadband technology has been dominated by developments on the receiver-side. Using new multicomponent streamer technology, modern recording equipment does not only record the scalar pressure wavefield, but also measures the associated particle velocity vector. This measurement, proportional to the gradient of the pressure wavefield, enables the application of many novel seismic imaging techniques, providing a better resolution of the subsurface.

Although novel receiver-side techniques have solved many long-standing problems in marine seismic acquisition, only little progress has been made on the source-side. Since applying similar concepts and techniques on the source-side, would provide the same benefits there, the development of novel source-side techniques is now brought into focus. Especially in times of low oil prices, new technology and surveying techniques on the source-side could provide the necessary improvement of marine seismic acquisition in terms of seismic imaging and efficiency. One of these new techniques is the acquisition of seismic data with simultaneous source shooting. The research presented here addresses this research interest by developing novel encoding techniques for simultaneous source acquisition, with one goal being the generation of source-gradient data. Such data can be used to tackle some long-standing challenges of marine seismic acquisition.

1.1 The marine seismic method

The seismic method uses the principles of reflection seismology to gain knowledge about the Earth’s subsurface from reflected seismic waves. It requires a controlled seismic source that emits acoustic energy that then propagates through the subsurface. In land seismic acquisition, the most common sources include explosive sources, such as dynamite or seismic vibrators known as “Vibroseis”. The most common source for marine seismic surveying, by far, is the air gun. For conventional marine seismic acquisition, multiple air guns are employed in clusters or so-called arrays and activated or ‘fired’ together as a group. The energy emitted by the seismic source
travels through the subsurface and is reflected at interfaces that it encounters on its propagation path. The reflected energy is measured by receivers, which record the wavefield, from which the time taken to travel from the source to the reflector and back to the receiver can be extracted by identifying individual reflection events. Using an estimated velocity model of the seismic waves in the subsurface, these travel times can then be analysed and used to reconstruct the travel paths and build an image of the subsurface.

In marine seismic surveying, the sources are typically deployed behind a marine vessel at a depth of a few meters. When the air-gun sources are activated, the acoustic energy travels through the water column and into the subsurface as illustrated in Figure 1.1. The downgoing energy is reflected at interfaces of layers across which an impedance contrast exits. The acoustic impedance of a layer is the product of its seismic velocity and its density. The difference in the impedance of two layers defines the strength of the reflections. After being reflected, the energy travels back upwards, where it is recorded by pressure sensors, the hydrophones. These hydrophones are spaced at certain intervals of a few meters within the so-called streamers, which are long cables towed by the seismic vessels. Streamers are typically filled with a low-density fluid to make them neutrally buoyant and keep them afloat at a certain depth within the water. Since streamers can be very long, they are steered by fins and buoys. Although there are many similarities between seismic acquisition on land and offshore, one main difference in terms of acquisition geometry is that in marine streamer acquisition, the source is typically deployed at one end of the receiver geometry, whereas on land, the source position can be chosen freely at any desired location and is typically located at either end or mostly within a receiver geometry. Moreover, the seismic sensors on land, the geophones, can easily be deployed and are fixed at the same position during continuous surveying, whereas in marine surveys the streamers move along with the ship for each seismic measurement. However, marine seismic acquisition can also be conducted with ocean-bottom sensors that are placed directly on the sea floor, while a vessel with a seismic source attached passes over them (Berg et al., 2010; de Kok, 2012). Although this kind of marine seismic acquisition setup is used more often nowadays, particularly for monitoring purposes, marine streamer data acquisition is still by far the most widespread technique in seismic exploration.

The simplest streamer configuration is a 2D seismic acquisition with one source and one streamer attached to a marine seismic vessel passing over a subsurface structure as shown on the left of Figure 1.2. This is how marine seismic surveying started off only involving 10’s to 100’s of receivers. By traversing over a subsurface structure multiple times with adjacent ship tracks typically spaced more than 1 km apart, a
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Figure 1.1: Illustration of the marine seismic method: An air-gun source configuration towed behind a marine vessel at a specific depth sends out a source signal that travels through the water and the subsurface. The resulting wavefield is reflected at interfaces in the subsurface (indicated by a number of ray paths) and recorded by pressure sensors, the hydrophones.

coarse image of the subsurface can be obtained. Although a better resolution of the subsurface can be achieved by sailing an increasingly large number of times and more densely over the subsurface structure of interest, there is a practical limitation to the use of 2D seismic acquisition to image complex subsurface structures correctly, because of its limited 2D illumination nature. To overcome this limitation and to improve seismic efficiency, multiple streamer acquisition methods have been developed for 3D seismic acquisition and have become the standard for marine surveying (Davidson and Bandell, 1990; Cramer et al., 1995). By passing over the subsurface structure with multiple streamers attached to the marine vessel, much more data is generated per sail line than for single-streamer 2D sail lines. The surveying of a subsurface structure suggested by the dashed contour lines in Figure 1.2 with a 2D acquisition setup compared to a 3D acquisition setup illustrates the advantage of the multiple streamer acquisition in terms of covering a large subsurface area and resolution. By utilizing more than one source and many streamers from the same
1.1 The marine seismic method

Figure 1.2: Left: 2D acquisition geometry vs. 3D acquisition geometry. The dashed lines are contour lines suggesting a subsurface structure. Assuming that the area covered by both survey geometries is the same, it is obvious that the 3D acquisition setup yields a better coverage and resolution of the subsurface structure. Right: Sail line pattern of a 3D acquisition campaign. Each line represents a ship track line. The acquisition vessel acquires seismic data along one line, then skips over several lines and tracks back down another line.

Seismic vessel, considerable gains in efficiency have been made. The acquisition of many closely-spaced subsurface 2D lines can thereby be achieved by a single sail line and multiboat operations enable the acquisition of wide-azimuth data (Sandø and Veggeland, 1995).

A typical acquisition pattern of a 3D seismic survey is shown on the right of Figure 1.2. Each line represents a sail line with the vessel acquiring data along one line, then skipping over a number of lines and sailing back down another line. Since 3D seismic acquisition campaigns are very expensive and take a long time, they require
careful preparation. Potential subsurface targets, for instance for hydrocarbon exploration, are generally identified beforehand by 2D seismic exploration. The best direction of the acquisition sail lines is then determined based on the assumed dominant subsurface dip and strike direction (Larner and Ng, 1984; Manin and Hun, 1992). The size of a 3D survey either refers to the number of square kilometers covered or, in the case of 2D acquisition, to the number of line kilometers acquired. A typical small 3D survey is on the order of a few hundreds of square kilometers and larger 3D surveys can cover up to a few thousand square kilometers.

Starting off with the first twin streamer operation in the 1980’s, modern seismic vessels can now tow more than 20 streamers with separations of 50 to 150 m. Figure 1.3 shows a conventional 3D seismic spread with 10 streamers plotted over the city of Zurich (scale 1:1) to illustrate the dimension of a modern marine seismic acquisition campaign. The air-gun sources (green) are towed directly behind the seismic vessel, which is typically on the order of 60–130 meters long and 20–70 meters wide, depending on the number of streamers that can be deployed. The streamers (orange), housing the recording sensors, are typically 6–8 km long in the inline or sailing direction. In the crossline direction, the seismic spread measures ca. 1–1.5 km and the streamers are kept apart by buoys and steering devices equipped with fins (red). With these tremendous towing configurations, marine seismic acquisition setups can be considered as the largest moving, man-made objects on Earth. One fundamental challenge of seismic acquisition at this scale is the steering of the streamers (Bittleston et al., 2000) and it is also obvious that it takes a wide area for the whole acquisition setup to turn; this also explains the acquisition pattern shown in Figure 1.2. With survey areas of a few thousand square kilometers to cover and a typical vessel speed during acquisition of 2–3 m/s, 3D seismic surveys can take many months to complete and require an enormous amount of logistic planning.

With the increasing number of streamers, the number of seismic recording channels has also significantly increased. Figure 1.4 shows the evolution of marine seismic channels from a few tens during the first seismic acquisition campaigns in the 1970’s to more than 100,000 in modern seismic surveys. According to the so-called “Moore’s law” for marine seismic channels (Monk, 2012), the number of recording channels in marine seismics doubles every 4.5 years. The tremendous data volumes of thousands of terabytes acquired during such a campaign require supercomputers to process the data in order to produce 3D images of the subsurface.

Traditionally, a certain number of hydrophones, measuring the pressure wavefield in the water usually with a 1 m spacing, are hard-wired into receiver groups of 12.5 or 25 m in length. The analogue array response of each receiver group is then digitized and sent to the recording device on the seismic vessel. This group forming
Figure 1.3: Conventional 3D seismic spread with 10 streamers (orange) plotted over the city of Zurich for the illustration of the dimensions of a marine seismic acquisition setup (scale 1:1). The seismic vessels tow the streamers with a separation of approx. 100–150 m and a length of 6–8 km and the seismic air-gun sources (green). (Image Source: ETH-Bibliothek Zürich*)
1 General Introduction

aims at attenuating in-line, water-borne noise and provides a spatial anti-alias filter of the seismic data. In modern receiver technology, the digitized data from each individual hydrophone sensor is sent directly to the vessel where a dynamic digital group-forming is performed depending on the present noise situation (Martin et al., 2000). This also enables the application of advanced filtering techniques, which has led to the acquisition of seismic data in so-called coil-shooting surveys, where the seismic vessel moves in a circular pattern (Moldoveanu, 2008).

The development of advanced acquisition technology in the last decades and the significant improvement of the control of receiver positions has enabled the application of time-lapse seismics. The term time-lapse seismics or “4D” seismics describes the repetition of a seismic survey at the same geographical location, but at a later time. Any changes in the subsurface result in changes of the recorded 3D seismic data. Any differences in the observed seismic image of a hydrocarbon reservoir can therefore be interpreted e.g., as fluid movement (Fayemendy et al., 2012). Since these changes in the reservoir are very subtle, new imaging techniques providing better resolution of the subsurface can significantly improve the comparability of repeated surveys.

1.2 Marine seismic sources

The marine seismic air gun is by far the most commonly used marine seismic source today. The concept of the air gun was developed in the 1960s at Lamont Doherty Earth Observatory at Columbia University with the primary motivation to find a safe and reproducible alternative to dynamite (Ewing and Tirey, 1961). Subsequently, the air-gun technology was developed into a commercial seismic source (Robertsson et al., 2015) and is nowadays used almost exclusively for marine seismic acquisition. Although other chemical, mechanical, pneumatic/hydraulic and electrical source concepts for marine seismic surveying have been explored in the past, they all suffer from various limitations and have not been developed into broadly available commercial offerings. The only other source that has lately been brought into the focus of research again is the marine seismic vibrator, which could potentially provide a number of geophysical and environmental advantages if sufficient low-frequency output could be generated (e.g., Tenghamn, 2006).

Air-gun sources

The air gun comprises a chamber of highly compressed air with an opening vent. This opening vent is sealed by a triggering piston and high pressure air is supplied
1.2 Marine seismic sources

Figure 1.4: Moore’s Law for the evolution of the number of recording channels in marine seismic acquisition. The trend line shows a doubling approx. every 4.5 years (after Monk, 2012).

into the chamber from a compressor onboard the seismic vessel. When the source is activated by releasing the piston, the high pressure air is rapidly discharged into the water forming a bubble which oscillates in the water. The air bubble expands and contracts multiple times in the water before it dissolves or breaks the surface. This oscillation of the air bubble generates the sound wavefield that is radiated away from the air gun. The oscillation period of the bubble depends on the firing pressure, the source depth and the air-gun volume. The physical process behind this bubble oscillation is described in detail by Parkes and Hatton (1986).

In conventional marine seismic acquisition, seismic air guns are usually employed in arrays. By using guns with different characteristics (gun volume, etc.) within an array the shape of the outgoing source pulse as well as the directivity pattern can be optimized. Additionally, by combining multiple air guns the total energy radiated can be increased (Laws et al., 1988; Dragoset, 2000). In practice, an air-gun array is composed of sub-arrays or “strings” of air guns of different firing volume, which are suspended from a floatation device at the desired depth below the water surface.
Figure 1.5 shows the side view diagram of a typical air-gun subarray. The presented subarray consists of a string of 8 air guns. The first two air-gun configurations on the left contain 4 air guns and each form a 2-gun cluster, which are activated together and considered as one source signature, so that this subarray yields 6 different air-gun signatures. The floatation device (yellow) at the sea surface carries a GPS positioning system providing information about the horizontal source position. An acoustic pinger provides additional information about the exact source position and communicates with the acoustic positioning system of the whole survey. Modern source configurations are also equipped with near-field hydrophones measuring the near-field signatures of the individual air guns. As shown by Ziolkowski et al. (1982) and Parkes et al. (1984) these near-field hydrophones can be used to determine the notional source signatures to eventually compute the far-field output of the air-gun source array in any direction.

An air-gun source array is typically made up of three subarrays, which are deployed parallel to each other. Conventional marine seismic surveys are often conducted with two air-gun source arrays positioned next to each other in a port and starboard position and used in a “flip-flop” shooting mode with alternating firing from shot to shot to reduce the crossline CMP (Common midpoint) spacing. This air-gun array configuration is also depicted in Figure 1.3. It is also important to note, that air-gun arrays are not point sources. Typically having dimensions of 10–25 m in inline and crossline direction (Dragoset, 2000; Calderón Agudo et al., 2016) they are associated with complex radiation patterns.

In recent years, the use of seismic air-guns has been partially limited and even banned in certain areas due to their environmental impact, especially on marine mammals (Richardson, 1995; Caldwell and Dragoset, 2000). These limitations have led to the development of more environmentally-friendly air-gun designs (Gerez et al., 2015) and they have revived the development of the marine vibrator technology (Pramik, 2013). Since the energy of a marine vibrator source is spread out over a much longer time than that from an air-gun array, the radiated instantaneous sound pressure level is much lower. Although the operational concept of using hydraulic or electrical power to drive an actuating plate in a controlled, oscillatory manner provides sufficiently high amplitudes in the mid-frequency range, the broadband output of a vibrator source is still considerably less compared to an air-gun array. However, considering current efforts to improve the low- and high-frequency output of the marine vibrator source, it might only be a matter of time until it becomes commercially available (Pramik et al., 2015; Wei, 2015).
1.2 Marine seismic sources

Figure 1.5: Side view of an air-gun subarray. This air-gun subarray contains 8 air guns in total. The first 4 air-guns on the left form 2-gun clusters such that this air-gun subarray is associated with 6 notional air-gun signatures. The yellow tube at the top provides floatation and swims at the sea level. The guns are suspended below at the specified operating depth and are supplied with compressed air from the seismic vessel. The position of the air-gun subarray is recorded by a GPS positioning system and an acoustic pinger. Near-field hydrophones are used to record the air-gun signatures.
1.3 Challenges for marine seismic acquisition

The quality of marine seismic data is limited by a number of factors. First, swell noise or noise caused by bad weather conditions impair the data quality. Interfering noise due to other seismic crews in the acquisition area (requiring thorough time-sharing management) and acoustic emissions from nearby drilling rigs or the seismic vessel and the recording equipment themselves are also potential noise sources. Efforts to overcome the noise problem on the receiver-side include single receiver recording and digital group forming techniques as well as towing streamers deeper to avoid wave action.

A second fundamental limitation in reflection seismology is caused by the traditional marine seismic acquisition geometry. Large, complex subsurface targets, such as salt structures and features of the shallow subsurface have a large influence on the raypath. The still predominantly 2D like nature of the acquisition geometry with long streamers with limited aperture positioned behind the air-gun sources causes illumination problems of complex subsurface structures. This illumination problem has been addressed by the acquisition of multi- or wide-azimuth data or by circular acquisition patterns (Moldoveanu, 2008).

Third, the bandwidth of the seismic source is limited by several processes and physical restrictions (e.g., bubble effect, ghost reflection, high frequency attenuation, etc.). Since the focus of exploration industry is shifting towards deeper and more complex targets such as subsalt and sub-basalt, bandwidth considerations of the seismic signal become increasingly important. The low frequency content is not only relevant for penetration and resolution, but also critical for achieving stable inversion results. A fourth issue of seismic data acquisition is the insufficient lateral sampling of the wavefield on the surface which leads to signal and noise aliasing despite a high channel count.

1.3.1 The ghost reflection

There are a number of processes that compromise the bandwidth of the seismic source and of the received seismic signal. Among them are acquisition artefacts such as the source bubble effect (Ziolkowski et al., 1982; Parkes and Hatton, 1986) and near surface effects such as the sea state due to the weather conditions. However, among the most significant factors are the attenuation of the high frequency content of the wavefield as it travels through the Earth and the reflections from the water surface known as “ghosts” (illustrated in Figure 1.6). Since the air-water interface acts as an acoustic mirror with a reflection coefficient for pressure of approx-
1.3 Challenges for marine seismic acquisition

approximately −1, energy from marine sources travelling upwards towards the surface will be almost perfectly reflected. The pressure wavefield reflected back thus undergoes a polarity reversal. This downgoing ghost wavefield constructively and destructively interferes with the upgoing wavefield (Parkes and Hatton, 1986; Hill et al., 2006), which results in the characteristic bandlimited nature of marine seismic data with notches observed in the frequency spectrum as a function of source/receiver depth (and take-off/incidence angle). In the case of vertically propagating waves, these notches are observed at the following frequencies:

\[ f_n = n \frac{c_w}{2z}, \quad (n = 0, 1, 2, 3, ...) \]  

where \( c_w \) is the wavespeed in water and \( z \) is the source/receiver depth. The band-limiting ghost effect is observed on the source as well as on the receiver-side. Figure 1.6 illustrates the ghost effect on the receiver-side (left) and shows the typical notches observed in the seismic pressure spectrum as a function of receiver depth (right). Towing receivers at shallow depth (red curve) enables recording of high frequencies, but results in an attenuation of low frequencies, whereas data acquired with a deeper tow (blue curve) show notches in the high frequency spectrum. On the source side, the ghost effect favors deep tows to enhance the limited low-frequency output of air-gun sources (Parkes and Hegna, 2011a). However, this effect is counteracted by the bubble time period, which increases with decreasing source depth, favouring shallower firing depth in practice (Parkes and Hegna, 2011b; Landrø and Amundsen, 2014).

Since the seismic ghost affects the bandwidth, it also reduces the resolution of the seismic image, if not corrected for. Additionally, the presence of ghost reflections in the seismic image can lead to misinterpretation of the seismic sections. The ghost effect for seismic imaging is similar to the reflection observed in a double-glassed window, which appears blurred as the reflection from the outer and inner glass overlap and cannot be distinguished easily by the human eye (Figure 1.7). The removal of the undesired reflections in photographs taken through glass windows is a comparable problem to deghosting in seismics, as these photographs also contain the desired scene and the undesired reflection (Shih et al., 2015).

To overcome the limitations imposed by the ghost reflection and to obtain broader bandwidth seismic data, novel marine acquisition technologies have been developed. The majority of these methods fall into two main categories: multi-level methods and gradient-based methods. Multi-level methods aim at the deployment of sources and receivers at different depth levels to generate and record seismic data with different notch characteristics. Gradient-based methods use multicomponent data recordings.
and dipole source approximations to perform a wavefield separation and recover the broadband seismic signal.

Addressing the bandwidth problem on the receiver-side requires taking complementary measurements of the recorded wavefield. New lateral positioning and steering technology allows to record data with two streamers towed one above the other (over/under) (Hill et al., 2006; Moldoveanu et al., 2007; Kragh et al., 2009), such that data recordings at different depths are obtained. These additional measurements can be combined to perform deghosting on the receiver-side. Whereas these multi-level methods are still based on conventional marine streamer acquisition with hydrophones measuring the scalar pressure wavefield, multicomponent methods rely on dual-sensor measurements recording the pressure wavefield as well as the vertical particle velocity using accelerometers (Carlson et al., 2007; Day et al., 2013). Combining the recorded pressure wavefield, $P$, and the vertical particle velocity, $V_z$, enables the separation of the recorded wavefield into its up- and downgoing components:

$$P^{up} = \frac{1}{2} \left( P - \frac{\rho c k}{k_z} V_z \right), \quad (1.2)$$
1.3 Challenges for marine seismic acquisition

Figure 1.7: Illustration of the marine seismic ghost effect for subsurface imaging: The ghost effect can be compared to the reflection observed in double-glassed windows. The overlapping reflections from the outer and inner glass of the window cause a blurry image. Similarly, the resolution of the seismic image is reduced by the interference of the direct upgoing wavefield and the reflected receiver ghost wavefield.
\[ V_{z}^{up} = \frac{1}{2} \left( V_{z} - \frac{k_{z}}{\rho c k} P \right), \]  

where \( P^{up} \) and \( V_{z}^{up} \) are the upgoing pressure and vertical particle velocity respectively, \( k = \omega / c \) is the wavenumber with \( \omega \) the angular frequency and \( c \) the velocity of sound in water, \( \rho \) is the density and \( k_{z} \) is the vertical wavenumber (Amundsen, 1993).

### 1.3.2 Spatial sampling and full-wavefield acquisition

In conventional marine seismic acquisition a scalar pressure wavefield is recorded along streamers. Limited sampling both on the receiver- as well as on the source-side results in spatially aliased data as illustrated in Figure 1.8. While on the receiver-side the spatial sampling is predominantly limited by the spacing of the seismic streamers in the crossline direction, the limitation on the source-side arises from the time that needs to pass between subsequent source shots. Since a brute force approach to denser sampling intervals for these two scenarios is challenging, new, fundamentally different techniques are required to address spatial sampling and aliasing.

A new concept for reconstructing the seismic wavefield, which relies on an observation which relaxes the sampling criterion by a factor of two or three, has been proposed by Robertsson et al. (2008a). Using the equation of motion, the particle motion recordings can be related to the spatial gradient of the pressure wavefield according to:

\[ \nabla P = i \rho \omega \vec{V}, \]  

where \( P \) is the pressure wavefield, \( i = \sqrt{-1} \), \( \rho \) is the density of water, \( \omega \) is the angular frequency and \( \vec{V} \) is the particle velocity vector. Robertsson et al. (2008a) discuss how the required additional measurements of the wavefield could be obtained with a multicomponent streamer, which includes not only hydrophones measuring the scalar pressure wavefield, but also particle motion sensors (accelerometers) to measure the three components of the particle motion vector. Figure 1.8 illustrates how these measurements of the gradient of the wavefield in addition to the scalar quantity of the pressure enable the reconstruction of signal, that would otherwise be irrecovarably aliased. Since the introduction of the commercial multicomponent streamer system IsoMetrix\textsuperscript{TM} (from WesternGeco), which uses both hydrophones and micro-electromechanical accelerometers, multicomponent data can now be recorded and used for deghosting and wavefield reconstruction to overcome the crossline sampling problem (Robertsson et al., 2008a; Özbek et al., 2010; Vassallo et al., 2010).
1.4 Source-side developments

Figure 1.8: Illustration of spatial aliasing resulting from insufficient sampling of the seismic wavefield and the benefit of gradient data for wavefield reconstruction. Top: The insufficient spatial sampling of the scalar pressure wavefield results in a spatially aliased sinusoid (red curve). The actual sinusoid (blue curve) has identical pressure values at the sample positions (black dots). Bottom: If the gradient of the wavefield is measured as well, the correct wave can be distinguished from the possible aliased replicas (modified after Vassallo et al. (2010)).

1.4 Source-side developments

All previously discussed challenges for marine seismic acquisition: noise, illumination, bandwidth and signal aliasing have been addressed by the introduction of new acquisition technology. Whereas many advances mainly have been related to the receiver-side of the problem (e.g., cross-line sampling), feasible solutions for the source-side have been missing, with the exception of the illumination problem, which has been resolved by illuminating complex targets from different azimuths.
This caused marine seismic acquisition to move from narrow-azimuth (NAZ) data recorded by a single vessel on a single pass to wide- and rich-azimuth acquisition (WAZ and RAZ) (Kapoor et al., 2007). The repeated illumination of the subsurface by acquiring data in different directions during multiple runs and by multiple shooting source vessels is also known as multiple azimuth acquisition (MAZ). The latest step of this development is the acquisition of full-azimuth, far-offset data in a coil-shooting pattern (Moldoveanu et al., 2012) and the acquisition with simultaneous sources discussed in the next section.

As stated by Robertsson et al. (2012), the subelements of marine seismic sources (air guns or explosive sources) can be regarded as emitting a monopole wavefield. The radiation characteristics of this monopole wavefield are equivalent to the measurement of the (omnidirectional) scalar pressure wavefield on the receiver-side. Since particle velocity measurements can be considered as elements of dipole character, respective dipole sources could provide comparable source-gradient data enabling similar benefits on the source-side as multicomponent recordings on the receiver-side (Robertsson et al., 2012; Halliday et al., 2012). Robertsson et al. (2008b, 2012) discuss how these dipole sources could be approximated by combining two closely-spaced monopole sources radiating the same wavefield with opposite polarity. Considering the acquisition of all four different source components with four-component (4C) receiver technology would thus result in the acquisition of 16-component (16C) source/receiver data. If the necessary dipole source data could be acquired, this full wavefield vector-acoustic sampling could provide a new paradigm in marine seismic acquisition providing significant benefits for solving some of the aforementioned challenges (Halliday et al., 2012).

Source-side deghosting methods are predominantly making use of sources deployed at different depth levels associated with different ghost notch frequencies. One approach is the over/under technique, which removes the source ghost by the combination of two independently recorded sources fired at different depths during subsequent processing (Moldoveanu, 2000). The more common approaches for broadband acquisition nowadays rely on dual-depth (Hopperstad et al., 2008) or multi-depth air-gun sources (Shen et al., 2014; Telling et al., 2014) that align the downgoing wavefield and attenuate the source ghost by destructive interference. Source-side deghosting methods based on multicomponent sources are still posing a challenge for marine seismic data acquisition. Although the acquisition of marine dipole source data has been discussed (Robertsson et al., 2008b) and could provide promising benefits for broadband acquisition, actual marine dipole sources do not exist yet or are in an early stage of development (Meier et al., 2015). In practice, this can be achieved by subtracting the data acquired from two close shot positions. Success-
1.5 Simultaneous source acquisition

fully separated simultaneous-source data acquired with reconfigured, conventional acquisition configurations could easily provide such data with little additional cost as demonstrated in Chapter 2 of this work. Halliday (2013) provides a comparison of the different source-side deghosting methods and comes to the conclusion that gradient-based methods could be most efficient for source-side deghosting.

1.5 Simultaneous source acquisition

In conventional seismic data acquisition, the energy decay rate and the depth of the target determine the time that needs to pass until the next source can be fired, as the signal from two adjacent shots must not interfere to avoid noise (Landrø, 2008). This listening time restricts the shot time interval and the minimum speed of the seismic vessel to ensure that streamers can be well controlled imposes a limit for the spacing between source locations (Figure 1.9). This fundamental limitation of the data acquisition rate has lead to the development of simultaneous source acquisition methods (Beasley et al., 1998; Berkhout, 2008; Moore et al., 2008; Ikelle, 2010). In simultaneous source acquisition, one or more additional sources are fired together or with a short time delay (Vaage, 2005; Stefani et al., 2007). The additional sources can thereby be located either close to the other source or in a spatially offset position with an additional source vessel to enable the simultaneous acquisition of wide azimuth data as illustrated in Figure 1.9. Since current processing techniques are not designed yet to deal with simultaneous source data directly, the two or more interfering sources must be separated as if they were recorded in a conventional fashion. After the successful separation into the corresponding noninterfering single-source data, the conventional seismic data processing and imaging techniques can be applied. This process is referred to as simultaneous source separation or deblending. Instead of actively separating the simultaneous source data, novel processing methods that directly process the simultaneous source data and perform a “passive” separation were also suggested (Berkhout, 2008).

The potential benefits of simultaneous source acquisition are manifold, e.g.,:

1. The simultaneous acquisition of wide-azimuth data enables the illumination of the subsurface from multiple angles (Moore et al., 2008).
2. An enhancement of the spatial source-sampling can be achieved by the simultaneous acquisition of additional shot positions.
3. Overcoming the limitation imposed by the listening time enables reducing the survey duration due to shorter times between successive shots, thereby also resulting in a major cost reduction and a significantly improved acquisition efficiency (Berkhout, 2008).
4. Finally, simultaneous source acquisition
techniques may enable the efficient generation of source-gradient data (Robertsson et al., 2008b), if the individual source responses from multiple simultaneous sources could be reliably separated. This could also boost the development and application of source-gradient techniques, which could bring the aforementioned benefits of multicomponent receiver data to the source-side enabling not only source-side reconstruction and deghosting applications (Robertsson et al., 2008a; Halliday et al., 2012), but also novel vector acoustic imaging techniques (Vasconcelos, 2013). This has been one of the principle motivations and goals of this thesis to explore.
1.5 Simultaneous source acquisition

1.5.1 Simultaneous source separation

The initial simultaneous source separation methods for marine seismic acquisition were based on known spatial filtering techniques employed for noise attenuation. One of the first to propose such a simultaneous source separation method was Beasley et al. (1998). Their separation method requires a substantial spatial separation of the simultaneous sources in order to separate them by normal moveout discrimination. An important extension of this observation was discussed by Long et al. (2013) for the simultaneous acquisition of long offset data. Other simultaneous source acquisition and separation techniques rely on the separability of the interfering seismic signal based on coherency (Lynn et al., 1987). These separation methods use source firing delays where one source is fired with a random but known time delay to separate the overlapping signal (Akerberg et al., 2008; Moore et al., 2008; Ibrahim and Sacchi, 2014). A novel insight into sampling of wavefields with applications to simultaneous source separation was proposed by Robertsson et al. (2016), who utilize a periodic sequence variation of the source signature from shot to shot along a sail line (e.g., time delay and amplitude variation), such that a known scaled portion of the corresponding wavefield is visible in a part of the spectral domain which does not overlap with the simultaneous source and thus can be separated.

The majority of the simultaneous source separation techniques applied nowadays make use of the coherency-based approach and are generally formulated as inverse problems, whose solution requires the definition of a set of basis functions that map the data into a domain in which the coherent energy is sparse. The secondary simultaneous source is typically fired with a random time delay of up to half a second which is varied from shot to shot. For the separation into non-interfering source data, the data are sorted into a domain that constitutes multiple simultaneous source shots, for instance into common offset gathers. Aligning the traces for the firing time of one source makes the energy associated with that source coherent, whereas the energy of the time-delayed source is incoherent. Figure 1.10a shows a common offset gather of a simple, synthetic simultaneous source dataset. The traces are aligned such that the firing time of source 1 corresponds to time zero and the three reflection events associated with this source are coherent. The energy associated with source 2 is incoherent.

In a next step, a Radon transform is performed to map the data into the $\tau$–$p$ domain (e.g., Hampson, 1986; Russell et al., 1990; Zhou and Greenhalgh, 1994; Moore and Kostov, 2002). For data sorted into common offset gathers, a linear Radon (tau-p) transform is applied summing the energy along straight lines defined by their intercept time, $\tau$, with the y-axis and their slowness, $p$, (i.e. dipping direc-
1 General Introduction

Figure 1.10: Illustration of simultaneous source separation with linear tau-p transform and sparse Radon inversion: a) Common offset gather of simultaneous source data in source 1 firing time. The events of source 1 are coherent, while the events of source 2 are incoherent due to the dithering. b) The linear Radon transform maps the data into the tau-p domain, where the coherent events are sparse, while the incoherent data are not sparse. c) The sparse Radon inversion solves for the strongest components in the tau-p domain, retaining only the sparse, coherent events. d) After a certain number of iterations, the separated data for source 1 is reconstructed from its sparse tau-p model.
1.5 Simultaneous source acquisition

Figure 1.10b shows the data of Figure 1.10a transformed into the linear tau-p domain, where the coherent events map to sparse points given by their intercept time and slowness, while the energy associated with source 2 is not coherent and thus does not yield a sparse tau-p model.

For the separation, the sparsity of the coherent energy in the tau-p domain is exploited using sparse inversion algorithms. By constraining the number of nonzero model components, these inversion algorithms promote sparsity of the Radon models, retaining only the coherent energy and thereby separating the simultaneous source data (Moore et al., 2008; Ibrahim and Sacchi, 2014). Figure 1.10c shows the tau-p model that is obtained after performing a sparse Radon inversion of the simultaneous source data in Figure 1.10a. In practice a sparse Radon inversion requires first a computation of the full tau-p model, such that the strongest components can be identified and selected based on a predefined threshold. The sparse inversion is then performed solving the inverse problem only for these components. For the simultaneous source separation problem, the inversion for sparse Radon models for all sources separates the data and the non-interfering data can be reconstructed as if recorded by conventional marine seismic acquisition using single-source shooting. Figure 1.10d shows the reconstructed source 1 data from the respective sparse Radon model in Figure 1.10c. It is important to note that the sparse inversion is applied iteratively. The first iterations separate the strongest events of the sources. These are then subtracted from the simultaneous source data so that also the weaker events can be separated from the residual with the sparse inversion method. The basic steps of a coherency-based simultaneous source separation method using a sparse Radon inversion algorithm for two simultaneous sources are shown in a flowchart in Figure 1.11. Sparse Radon inversion is not only used for solving simultaneous source separation problems, but has also been applied to many other geophysical problems such as noise or multiple removal (Russell et al., 1990; Trad et al., 2003).

1.5.2 Encoding of seismic sources

The idea of encoding seismic sources was first established for the acquisition of land seismic data using seismic vibrator sources. The introduction of the Vibroseis technology in the 1960’s provided for the first time a seismic source that could at least partly be controlled in terms of its frequency output. Since seismic interference from other seismic crews or seismic noise sources have always been an issue in seismic acquisition, novel encoding techniques that could help to suppress noise and improve the seismic signal quality were sought after. While the initial objective of controlling the Vibroseis source output was primarily the suppression of correlated
Figure 1.11: Flowchart illustrating the basic steps of the simultaneous source separation method based using a sparse inversion algorithm based on coherency. Although the method is illustrated here for two simultaneous sources, the methodology can easily be extended to include more than two simultaneous sources.
noise (Bernhardt and Peacock, 1978; Edelmann and Werner, 1982), the potential of encoding techniques for the parallel acquisition of multiple point sources, i.e. the simultaneous source acquisition, was soon realized (e.g., Martínez and Crews, 1987; Womack et al., 1990). Nowadays, encoding techniques are commonly used in conventional land seismic acquisition and different Vibroseis acquisition methods such as cascaded sweeps, slip sweeps and essentially simultaneous shooting have been established (Bagaini, 2006). A thorough overview of how the Vibroseis signal can be controlled and which encoding techniques can be used for simultaneous source acquisition on land is provided by Dean (2014).

For marine seismic acquisition, encoding techniques for marine seismic sources have not been used in acquisition, but their discussion has just recently been revived. The main reason why encoding techniques have not found their way to marine seismic sources yet, has been the lack of marine seismic vibrator technology. Although marine vibrator technology could possibly enable the application of the known encoding techniques for land seismic vibrator sources for marine acquisition, encoding techniques for well-established marine air-gun sources can also be developed and promise numerous benefits from improving simultaneous source separation to the generation of source-gradient data. The air-gun array has been the main source in marine seismic acquisition for many decades. The individual air guns of the array are generally fired at almost the same time. This concept of tuning the air-gun array to yield a sharp source pulse and cancel the bubble effects of the different air-gun firing volumes was undisputed for a long time. Although the idea of firing an air-gun array sequentially has been discussed in the past by Stoffa and Ziolkowski (1983) and Ziolkowski (1984), it was not followed up for seismic acquisition. However, the idea of sequential air-gun shooting has been brought up again by Robertsson et al. (2008b) who suggest to use encoding sequences for simultaneous source acquisition. Choosing sequences that are close to orthogonal to each other, having minimal cross-correlation and optimal autocorrelation properties, would enable the exploitation of their orthogonality as a separation feature. In addition, the idea of detuning the air-gun array was also proposed for a single air-gun array. Abma and Ross (2013, 2015) suggest a “Popcorn shooting” method that distributes the air-gun array energy over time. Shooting the individual air-guns sequentially reduces the peak sound level output of the air-gun array and thereby reduces its environmental impact. These are all indications that the potential of encoding techniques for marine seismic sources is now being realized, but has not been fully explored yet. Particularly with the computational resources available nowadays, the necessary, computationally expensive sparse inversion algorithms can now be applied to large datasets to reconstruct the impulsive source data from encoded (simultaneous) source datasets.
1 General Introduction

1.6 Thesis outline

Bringing encoding techniques to marine seismic sources to enable source-gradient generation lies at the core of this thesis. We take on the idea of Robertsson et al. (2008b) to encode marine seismic sources with firing sequences being orthogonal to each other. First, we demonstrate the benefit of sequence encoding for simultaneous source separation, enabling the acquisition of closely spaced source data. Then we develop an optimization method to design near-orthogonal air-gun firing sequences having the desired orthogonality properties. Finally, we apply the concept of sequence orthogonality to depth-distributed sources and suggest a source encoding that enables the separation of the source ghost as a separated source.

In chapter 2, we develop a method for simultaneous source separation using encoded source sequences in combination with time dithering. The source sequences are chosen to be close to orthogonal to each other. To guarantee this, we use firing sequences that are designed by convolving a source wavelet with Kasami sequences that are known to have optimal orthogonality properties. We find that using the sequence encoding of time-dithered sources can be exploited with a multifrequency separation method. The multifrequency separation method not only takes advantage of the sequence orthogonality, but it also allows dealing with realistic source intervals, which may result in spatially aliased data. Testing the method with realistic synthetic examples shows a reduction of the separation error using encoded source sequences compared to simultaneous source separation based on time dithering only by a factor of more than 2.

In chapter 3, we present a method to design air-gun firing sequences having the desired orthogonality properties. The proposed optimization method is based on a simulated annealing algorithm and optimizes the firing sequences to have minimized crosscorrelation and optimized autocorrelation properties. By the variation of the firing times of individual air guns, different encoding sequences are constructed and their orthogonality properties are evaluated by a cost-function that is minimized as part of the optimization procedure. This optimization approach enables the design of tailor-made air-gun firing sequences for multi-purpose applications. Particularly for simultaneous source separation it overcomes the limitation to rely on the orthogonality of random air-gun firing sequences and provides an additional improvement of the separation as shown by synthetic examples. We also demonstrate the robustness of the sequence-encoding method in terms of take-off angle variations and possible errors in sequence estimation.

Chapter 4 follows as a direct application of the sequence optimization method. We show that by distributing air guns over depth firing sequences can be designed
whose direct, downgoing wavefield is close to orthogonal to its source ghost wavefield. Generating a set of such firing sequences, so that they can be varied from shot to shot, enables the separation of this ghost-source wavefield as a separate source, the “ghost-source”. This concept cannot only be used for source deghosting, but also enables the simultaneous acquisition of two sources positioned vertically above each other that can be combined for the generation of vertical source gradient data.

Chapter 5 summarizes the results of the individual chapters and gives an outlook of how the combination of the findings of this work can be applied for full wavefield acquisition.

Chapters 2 and 3 are based on previous publications in the peer-reviewed journal GEOPHYSICS issued by the Society of Exploration Geophysicists. Chapter 4 will be submitted as manuscript to GEOPHYSICS given approval by the co-authors. This also explains why these chapters are self-contained and may include information which is to a certain extent redundant (also with respect to this introduction). The thesis is structured such that each chapter deals with one major step to achieve the main objectives towards full wavefield seismic acquisition. The title, list of co-authors, and the journal of these publications are noted in footnotes on the first page of each chapter.

References


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References


Monk, D. 2012. “An oil independents view on advances in petroleum industry seismic acquisition technology”. In *SEAPEX Conference*.


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Stefani, J., G. Hampson, and E. Herkenhoff. 2007. “Acquisition Using Simultaneous Sources”. In 69th EAGE Conference & Exhibition.


Chapter 2

The benefit of encoded source sequences for simultaneous source separation

Abstract

We present a method for simultaneous source separation using time-dithering and encoded source sequences. The source sequences are designed so that they are close to orthogonal to each other, having minimized cross-correlation and optimal auto-correlation properties. We show that this additional encoding of time-dithered sources can be exploited with a multifrequency separation method. The separation method relies on a coherency-based approach and is solved by sparse Radon inversion. Realistic synthetic data examples confirm the importance of using a multifrequency method to take advantage of the sequence orthogonality and to deal with spatially aliased data. Our results demonstrate that source sequence encoding can significantly improve simultaneous source separation compared to using timedithering only.

2 The benefit of encoded source sequences for simultaneous source separation

2.1 Introduction

In conventional seismic data acquisition, the shot time interval is limited by the energy decay rate and the depth of the target. This imposes a limit for the spacing between source locations and therefore the data acquisition rate, which has caused the seismic industry to consider simultaneous source acquisition methods (Beasley et al., 1998; Berkhout, 2008; Moore et al., 2008; Ikelle, 2010). For conventional seismic data processing and imaging techniques to be applied, the two or more simultaneous sources must be successfully separated into the corresponding non-interfering single source data (a process that is also known as simultaneous source separation or deblending). In contrast to active separation of simultaneous source (sim-source) data, “passive” separation methods, which do not separate the sim-source data before further processing were also suggested (Berkhout, 2008). The potential advantages of sim-source data are numerous, comprising benefits in terms of improved illumination, enhanced source sampling and essentially a significant improvement in acquisition efficiency (Moore et al., 2008). Furthermore, sim-source acquisition may allow the efficient acquisition of source-gradient data and may therefore boost the development and application of multicomponent marine source techniques (Robertsson et al., 2008b). These source gradient techniques are an important step to enable similar benefits for source-side deghosting and source-side reconstruction as seen on the receiver side by the introduction of the multicomponent streamer (Robertsson et al., 2008a; Halliday et al., 2012). In addition, acquisition of full wavefield vector acoustic data enables new imaging techniques that are capable of focusing energy from all in- and outgoing waves simultaneously (Vasconcelos et al., 2012; Vasconcelos, 2013).

One approach for sim-source acquisition and separation relies on the separability of the interfering seismic signal based on coherency (Lynn et al., 1987): for instance using source time dithering. Moore et al. (2008) and Akerberg et al. (2008) use source firing time delays to separate sim-source data, where one source is fired with random but known time delays. For the separation into the equivalent non-overlapping source data, the data are, for instance, sorted into common offset gathers, which constitute multiple sim-source shots, and the traces are aligned such that the firing time of one source corresponds to time zero. This makes the energy of this specific source coherent, whereas the energy associated with the second, time-delayed source is incoherent. The sim-source separation methods are generally posed as an inverse problem, whose solution includes the definition of a set of basis functions that map the data into a domain in which the coherent energy is sparse. The main category of these separation techniques is based on sparse Radon inversion (Akerberg et al., 2008; Moore et al., 2008; Ibrahim and Sacchi, 2014). Imposing a sparsity
constraint on the Radon model, by favoring the model that has the smallest number of non-zero components, helps to retain only the coherent energy and to separate the simultaneous sources (Cary, 1998; Trad et al., 2003).

In conventional sim-source separation with dithered sources, the known random time delays between the sources are the only a priori information that are used apart from the locations of the sources. Robertsson et al. (2008b) discuss the concept of encoding air-gun arrays by firing the air-gun arrays sequentially. Rather than activating each air-gun sub-element at the same time (i.e., a conventional, tuned air-gun array) to obtain a single sharp pulse, the sub-elements are fired independently over a period of time, yielding a sequence of impulses with reduced peak amplitude. The sequences can be chosen to be close to orthogonal to each other (i.e., to have minimized cross-correlation and optimal auto-correlation properties (maximized peak-to-side-lobe ratio)). This orthogonality of the sequences can then be used as an additional feature to separate the sim-source data. While using tuned air-gun arrays, the individual air-gun pops interfere to yield a broad spectrum, the discussed firing sequences have additional notches in their spectra due to spreading the air-gun signal over time. A similar approach for a single air-gun array was suggested by Abma and Ross (2013) who proposed reducing the peak amplitudes for minimal environmental disturbance. They demonstrated that this so-called “Popcorn shooting” method allows the equivalent impulsive source signal to be reconstructed using a sparse inversion method.

Here, we demonstrate how sim-source separation can be enhanced using encoded firing sequences. By using source sequence encoding on top of time dithering, we can exploit the orthogonality of the sequences using a multifrequency inversion approach. In this article, we show first that when a single frequency separation method is used, sim-source separation using time-delayed sources encoded with source sequences works equally as well as source separation using conventional, dithered sources (Mueller et al., 2014). We will then build on this result and adopt a multiple frequency separation method that was introduced by Ji et al. (2012, 2013). By using several frequencies to estimate the model for each frequency component, the algorithm allows us to exploit the full potential of sequence-encoded sources for sim-source separation. In addition, it allows us to deal with spatially aliased data and to fill notches in the spectra of the sequences. Ji (2014) has also demonstrated the potential of the frequency-diverse method in terms of notch-filling and overcoming spatial aliasing for 3D deghosting applications. In our synthetic examples, we use one set of optimized Kasami sequences (Fan and Darnell, 1996; Dean, 2014) that are transformed into bipolar sequences and convolved with a Ricker wavelet to simulate firing sequences with desirable orthogonality properties. These sequences are
not air-gun sequences, but they are used to demonstrate the potential of optimally designing such firing sequences. We do not consider varying sequences for each shot, because this implies a spatial encoding in addition to the temporal encoding, which makes it difficult to see the uplift associated with temporal encoding only.

2.2 Methodology: Separation Method

In simultaneous source acquisition, the seismic energy from different sources is recorded in one shot record. For simplicity, the separation approach is described here for two sources, although it is applicable to any number of sources. In the case of two sources, the data record is a combination of the energy $d_1$ and $d_2$ from the two sources $S1$ and $S2$, i.e., $d = d_1 + d_2$. In dithered sim-source acquisition, one source is fired regularly, while the second source is fired with random, but known time delays (Akerberg et al., 2008; Moore et al., 2008). For the separation process, the data are sorted into a domain that constitutes multiple shots with e.g., fixed offset/receiver, and the traces are aligned such that time zero corresponds to the firing time of one source. This makes the signal associated with this source coherent. This coherency can be exploited for the source separation, as the decomposition of the coherent signal by a Radon transform yields a sparse set of events, while the incoherent energy results in a diffuse cloud. In general, this composition of the data $d$ by a Radon model $m$ can be described with a set of basis functions $B = [b_1, ..., b_N]$ as:

$$d = Bm. \quad (2.1)$$

The majority of simultaneous source separation methods are posed as an inverse problem to estimate the model $m$ and can be formulated as:

$$\min \|m\|_q^q \text{ subject to } \|d - Bm\|_p^p \leq \epsilon. \quad (2.2)$$

where the parameters $p$ and $q$ indicate that different norms can be applied (Trad et al., 2003) and $\epsilon$ is a combination of some noise level and a residual due to the misfit of the estimated model and the data.

In our analysis, we sort the data into common offset gathers and test two separation methods, that are both applied in the frequency domain to estimate a Radon model for each frequency component of the data. The single frequency method uses only the respective spectral component for the separation, while the multifrequency method uses multiple frequency components to estimate a $\tau - p$ model for each frequency component.
2.2 Methodology: Separation Method

2.2.1 Single Frequency Method

The simultaneous source separation problem for time-dithered sources can be formulated following the approach by Moore et al. (2008) and Akerberg et al. (2008):

\[ d^{sf} = (A_1 W_1 \; DA_2 W_2) \begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = Bm, \]  

(2.3)

wherein \( d^{sf} = d^{sf}(\omega_j) \) is the single frequency data vector for the spectral component of the angular frequency \( \omega_j \) for all channels:

\[ d^{sf}(\omega_j, x) = \begin{pmatrix} d_{x_0}(\omega_j) \\ \vdots \\ d_{x_N}(\omega_j) \end{pmatrix}, \]  

(2.4)

with \( x \) the offset vector of the data traces ranging from \( x_n = x_0, ..., x_N \). \( W_s = W_s(\omega_j) \), for \( s = 1, 2 \), are the spectral frequency components of the corresponding source signatures for S1 and S2. The model vectors \( m_s = m^{sf}_s(\omega_j) \), for \( s = 1, 2 \), correspond to the respective estimated slowness models of the separated sources S1 and S2:

\[ m^{sf}_s(\omega_j, p) = \begin{pmatrix} m_{p_0}(\omega_j) \\ \vdots \\ m_{p_K}(\omega_j) \end{pmatrix}, \]  

(2.5)

with the vector of model slownesses \( p_k = p_0, ..., p_K \). \( A_s \), for \( s=1,2 \), are Radon operator matrices. Here, the source separation is tested on common offset gathers, in which it is assumed that the coherent energy can be represented by a sparse set of linear plane waves and, thus, linear Radon operators are used. The corresponding basis function vectors are given by:

\[ b^{sf}(x_n, p) = \begin{pmatrix} \exp(i \omega_j x_n p_0) \\ \vdots \\ \exp(i \omega_j x_n p_K) \end{pmatrix}. \]  

(2.6)

The linear Radon operators \( A_s \), for \( s = 1, 2 \), can then be defined as:

\[ A_s = \begin{pmatrix} b^{sf}(x_0, p) & \ldots & b^{sf}(x_N, p) \end{pmatrix}. \]  

(2.7)
These operator matrices must be capable of modelling the data with the specified intercept time and slownesses ranges. For the common offset data analyzed here, these ranges are chosen to be identical, so that $A_1 = A_2$. The diagonal matrix operator $D = D_{sf}(\omega, x)$ shifts the traces according to the firing delays of source S2 and guarantees the coherency of the source 2 energy for the respective part of the model space:

$$D_{sf} = \begin{pmatrix} \exp(i\omega j t_d(x_0)) & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & \exp(i\omega j t_d(x_N)) \end{pmatrix}, \tag{2.8}$$

where $t_d(x_n)$ is the vector containing the known firing time delay of source S2 for each trace.

After successful separation of the simultaneous sources into the respective models $m_s(\omega, p)$, the separated seismic data can be reconstructed with the linear modelling equations:

$$d_1 = A_1 W_1 m_1, \quad d_2 = A_2 W_2 m_2. \tag{2.9}$$

Instead of using tuned airgun sources, we may also encode the two sources using firing sequences, where each airgun “pop” corresponds to a spike in the sequences (Abma and Ross, 2013). Ideally, these “Popcorn-type” firing sequences are chosen to be orthogonal to each other, i.e., their auto-correlation response should have a maximized peak-to-side-lobe ratio, whereas the cross-correlation between the sequences should be close to zero. Although the cross-correlation between two finite-length signals with the same bandwidth cannot be eliminated, it can be minimized (Welch, 1974). This orthogonality feature can be exploited to separate the energy from the encoded sources (Robertsson et al., 2008b). In the separation problem, the encoding sequences are included as multiplications in the temporal frequency domain:

$$d_{sf} = (Q_1 A_1 \quad DQ_2 A_2) \begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = Bm, \tag{2.10}$$

where the coherence operators $A_1$ and $A_2$ are linear Radon operators according to Equation 2.7. $Q_s(\omega, x)$, for $s = 1, 2$, is a diagonal matrix containing the spectral
2.2 Methodology: Separation Method

frequency components of the respective source sequences used for each shot:

\[
Q_s(\omega_j, x_n) = \begin{pmatrix}
Q(\omega_j, x_0) & \ldots & 0 \\
\vdots & \ddots & \vdots \\
0 & \ldots & Q(\omega_j, x_N)
\end{pmatrix}.
\]  \(2.11\)

The source time shift of source S2 is accounted for by the diagonal matrix operator \(D = D^{sf}(\omega_j, x)\) (defined in Equation 2.8). This source time delay is required when the same set of firing sequences is used for each shot. If the firing sequences are changed for each shot position and each source, a source time delay of the secondary source is not essential for the source separation, i.e., \(D = I\) (In the following, this is not considered.).

The source separation into the models \(m_1(\omega_j, p)\) and \(m_2(\omega_j, p)\) in the linear systems of equations described in Equations 2.3 and 2.10 can be solved by different approaches. Key to most recent approaches is the objective to obtain a sparse model in the \(\tau - p\) model space with a limited number of non-zero model components. In practice, this Radon model is estimated for each single frequency by favouring the model with the smallest number of non-zero slowness components. We have tested different Radon transforms including the classical least-squares Radon transform with quadratic regularization and iterative algorithms such as the iteratively re-weighted least squares (IRLS) algorithm (Trad et al., 2003). Here, we use the IRLS algorithm for the single-frequency method.

2.2.2 Multifrequency Method

The multifrequency (or frequency-diverse) sim-source separation method was introduced by Ji et al. (2012, 2013). In contrast to the aforementioned single frequency method, this method uses multiple frequencies to compute the Radon model for a single frequency \(\omega_j\). The separation problem is formulated and solved in a way that is similar to the single frequency method, but the definition of the basis functions and the setup of the data vector and model vectors is more complex. In the case of dithered sim-source acquisition, the following linear system is considered:

\[
d^\text{mf} = (W_1A_1 \quad DW_2A_2) \begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = Bm.
\]  \(2.12\)

Assume that there are \(n\) channels and the position vector \(x\) ranges from \(x_0\) to \(x_N\). Following the approach of (Ji et al., 2012, 2013), \(2L + 1\) frequencies are used to
2 The benefit of encoded source sequences for simultaneous source separation

solve for the models \( \mathbf{m}_1(\omega_0) \) and \( \mathbf{m}_2(\omega_0) \). The data vector \( \mathbf{d}^{mf} \) now consists of the multichannel array response for multiple frequencies \( \omega_l, l = -L, ..., 0, ..., L \) and is written as:

\[
\mathbf{d}^{mf} = \begin{pmatrix}
  d_{x0}(\omega-L) \\
  \vdots \\
  d_{x0}(\omega_0) \\
  \vdots \\
  d_{x0}(\omega+L) \\
  \vdots \\
  d_{xN}(\omega_0) \\
  \vdots \\
  d_{xN}(\omega+L)
\end{pmatrix}.
\]  

(2.13)

The model vectors \( \mathbf{m}^{mf}_s \) with \( s = 1, 2 \) are written as:

\[
\mathbf{m}^{mf}_s(p_k, \tau_j) = \begin{pmatrix}
  m_s(p_0, \tau_0) \\
  \vdots \\
  m_s(p_0, \tau_J) \\
  \vdots \\
  m_s(p_K, \tau_0) \\
  \vdots \\
  m_s(p_K, \tau_J)
\end{pmatrix},
\]  

(2.14)

where \( \tau_j \in \tau_0, ..., \tau_J \) is the j-th component of the intercept row vector \( \mathbf{\tau} \) and \( p_k \in p_0, ..., p_K \) is the k-component of the slowness row vector \( \mathbf{p} \). The linear operator
matrices $\mathbf{A}$ are composed of basis function vectors of the form:

$$
\mathbf{b}_{mf}(p_k, \tau_j) = \begin{bmatrix}
\exp(i \omega_L u(p_k, x_0, \tau_j)) \\
\vdots \\
\exp(i \omega_L u(p_k, x_N, \tau_j)) \\
\exp(i \omega_0 u(p_k, x_0, \tau_j)) \\
\vdots \\
\exp(i \omega_0 u(p_k, x_N, \tau_j)) \\
\exp(i \omega_L u(p_k, x_0, \tau_j)) \\
\vdots \\
\exp(i \omega_L u(p_k, x_N, \tau_j))
\end{bmatrix}.
$$

(2.15)

These basis function vectors are of length $N \cdot (2L+1)$. The phase function $u(p_k, x, \tau_j)$ can be any type of function that describes the recorded energy. For a linear event, the phase function reads:

$$
u(p_k, x, \tau_j) = p_k \cdot x + \tau_j,
$$

(2.16)

with $\mathbf{x}$ being a column vector of the trace positions. The linear operator matrices $\mathbf{A}_s$ with $s = 1, 2$ can then be written with the aid of the basis function vectors $\mathbf{b}_{mf}(p_k, \tau_j)$ (defined in Equation 2.15):

$$
\mathbf{A}(p, \tau) = (\mathbf{b}(p_0, \tau_0) \ldots \mathbf{b}(p_0, \tau_J) \ldots \mathbf{b}(p_K, \tau_0) \ldots \mathbf{b}(p_K, \tau_J)).
$$

(2.17)

The diagonal operator matrix $\mathbf{D} = \mathbf{D}_{mf(\mathbf{x})}$ contains the respective time shifts due to the delays of source S2:

$$
\mathbf{D}_{mf(\mathbf{x})} = \begin{pmatrix}
\mathbf{D}(\mathbf{x})_{-L} & \ldots & 0 \\
\vdots & \ddots & \vdots \\
0 & \ldots & \mathbf{D}(\mathbf{x})_L
\end{pmatrix},
$$

(2.18)

where

$$
\mathbf{D}_l(\mathbf{x}) = \begin{pmatrix}
\exp(i \omega_l t_d(x_0)) & \ldots & 0 \\
\vdots & \ddots & \vdots \\
0 & \ldots & \exp(i \omega_l t_d(x_N))
\end{pmatrix}, \ l = -L, \ldots, 0, \ldots, L,
$$

(2.19)
where $\mathbf{t}_d(x)$ is the vector with the known S2 source time delays for each trace. The spectral frequency components of the source signatures for S1 and S2 are contained in the diagonal matrices $\mathbf{W}_s = \mathbf{W}_{s}^{mf}$ with $s = 1, 2$:

$$\mathbf{W}_s^{mf} = \begin{pmatrix} \mathbf{W}_{s,-L} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{W}_{s,L} \end{pmatrix}, \quad (2.20)$$

where

$$\mathbf{W}_{s,l} = \begin{pmatrix} W_s(\omega_l, x_0) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & W_s(\omega_l, x_N) \end{pmatrix}, \quad l = -L, \ldots, 0, \ldots, L. \quad (2.21)$$

Once the linear system of data and basis functions is set up, Equation 2.12 is solved with a variation of the matching pursuit algorithm, discussed in more detail at the end of this section, and the separated data are reconstructed by forward modelling of the Radon model estimate.

The multifrequency separation method for encoded source sequences follows closely the setup of the linear system of equations described for the time-dithered sources:

$$\mathbf{d}^{mf} = (\mathbf{Q}_1 \mathbf{A}_1 \mathbf{D} \mathbf{Q}_2 \mathbf{A}_2) \begin{pmatrix} \mathbf{m}_1 \\ \mathbf{m}_2 \end{pmatrix} = \mathbf{Bm}. \quad (2.22)$$

The multifrequency data vector $\mathbf{d}^{mf}$ is defined according to Equation 2.13 and the linear Radon operators $\mathbf{A}_1$ and $\mathbf{A}_2$ correspond to the setup described by Equations 2.15 and 2.17. The model vectors $\mathbf{m}_s^{mf}$ with $s = 1, 2$ are equivalent to the definition in Equation 2.14. The source time shift operator $\mathbf{D} = \mathbf{D}^{mf}$ (Equation 2.12) accounts for the shot time delays of source S2 and is required when time-delayed sources are used with the same set of firing sequences for each shot. Again, as for the single-frequency method, when different sets of firing sequences are used for each shot, source dithering can be omitted, $\mathbf{D} = \mathbf{I}$. The convolutional operators $\mathbf{Q}_s = \mathbf{Q}_s^{mf}$ with $s = 1, 2$ contain the spectral components of the source sequences for the respective traces:

$$\mathbf{Q}_s^{mf} = \begin{pmatrix} \mathbf{Q}_{-L} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{Q}_L \end{pmatrix}, \quad (2.23)$$
2.3 Synthetic Data Study

with

\[ Q_l(x) = \begin{pmatrix} Q_s(\omega_l, x_o) & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & Q_s(\omega_l, x_N) \end{pmatrix}, l = -L, \ldots, 0, \ldots, L. \quad (2.24) \]

The multifrequency method described in detail by Ji et al. (2013) has numerous benefits for simultaneous source separation. Foremost, it can improve the separation when dealing with spatially aliased data by combining the array response of multiple frequencies when solving for a single frequency model (Ji, 2014). It can therefore be considered as being in between a single-frequency method and a full time-domain solution. Working with several frequencies simultaneously also enables us to fill the notches of the source sequences from neighboring spectral components and allows taking advantage of the orthogonality properties of the sequences for source separation.

For the separation with the multifrequency method, we use a variation of the matching pursuit algorithm that solves for the strongest components in the Radon model space and iterates on the residual of the data. Our implementation starts by computing the adjoint Radon transform of the data, expressed as:

\[ m = B^T d, \quad (2.25) \]

where \( B \) is the corresponding set of basis functions as defined in Equations 2.3 and 2.10. Then we choose the strongest model components of the source models \( m_1 \) and \( m_2 \) and solve the inverse problem (Equation 2.2) with a classical least-squares (LSQR) algorithm for only these strongest components. This typically yields a sparse Radon model that contains only the coherent events, which are then reconstructed with a forward Radon transform. This approach is applied iteratively to the residual of the data and solved for the strongest remaining components until a maximum number of iterations is reached. The separated shot records can then be reconstructed according to Equation 2.9.

2.3 Synthetic Data Study

We test the source separation methods on realistic synthetic data of a 2.5 D model, which is loosely based on North Sea geology. Figure 2.1 shows the corresponding P-wave velocity model containing three tilted fault blocks and a flat spot in the central fault block. Synthetic shot records for sources at 6 m depth and receivers at
The benefit of encoded source sequences for simultaneous source separation

Figure 2.1: P-wave velocity model of North Sea geology: The dashed box marks the focus area that is considered for sim-source separation.

20 m depth were modeled with a finite-difference code without a free surface. The shot records are generated with a time sampling of $\Delta T = 4$ ms and a Ricker source wavelet with central frequency $f_c = 50$ Hz. The data are then sorted into common offset gathers with a source spacing of 40 m. The positions of the second source were chosen in-between the shot positions for source 1, i.e., at a 20 m offset position.

The synthetic sim-source data are generated by addition of the shot record for source 1 and the shot record of source 2 (from a position offset of 20 m) with a time shift corresponding to the time dithering. For each shot, a random time delay of $+100$ to $+500$ ms drawn from a uniform distribution was chosen for source 2. The performance of the separation methods is evaluated with common offset data with an offset of 500 m on a window including the fault blocks as indicated by the dashed box in Figure 2.1. The corresponding common offset gathers for source 1 and source 2 and the dithered sim-source data are shown in Figure 2.2. Figure 2.2c is the F-K spectrum of the source 1 data (Figure 2.2a) and shows that there is significant spatial aliasing in the 40 m common offset data. With the slowest apparent velocity in the
2.3 Synthetic Data Study

![Figure 2.2](image)

**Figure 2.2:** 500 m Common offset data of the area of interest: (a) Source 1 in source 1 firing time, (b) Source 2 in source 2 firing time, (c) F-K Spectrum of source 1 data, (d) Dithered sim-source data in source 1 firing time.

common offset data being $v_{app} \approx 4000$ m/s, we start to observe an alias factor of 1 above frequencies of $f_{app} = 50$ Hz.

For the encoding of the sources, we choose a set of binary Kasami \{0, 1\} sequences that are transformed into bipolar \{+1, −1\} sequences (Fan and Darnell, 1996). These bipolar sequences are convolved with a source signature to simulate encoded firing sequences. Here we use a set of sequences with a length of 256 samples (Figure 2.3a
and b) and convolve it with a Ricker wavelet with central frequency $f_c = 50$ Hz. With a time sampling of 4 ms, the resulting sequences are approximately 1 s long (Figures 2.3c and d). Their autocorrelations (Figures 2.3e and f) show sharp peaks with comparably low sidelobes and their crosscorrelation (Figure 2.3g) is of comparably low amplitude so that the sequences can be considered close to orthogonal to each other.

The sequence encoded data for source 1 (Figure 2.4a) are generated with the sequence shown in Figure 2.3c. The sequence in Figure 2.3d is used to encode the data for source 2 and the same source time shifts as for the time-dithered data in Figure 2.2 are applied as source time delays. Figure 2.4b shows the dithered, sequence-encoded data of source 2 and Figure 2.4c shows the dithered, sequence-encoded sim-source data, which are the sum of the single source records in Figure 2.4a and b.

### 2.3.1 Separation with a single-frequency method

First, we use the single-frequency method to separate the dithered sim-source data in Figure 2.2. As the energy in these data is not coherent over the whole window of 50 traces with a 40 m offset, we subdivide the data into five non-overlapping windows of 10 traces each and process these data windows individually. For the source separation with the single-frequency method, we use an Iteratively Reweighted Least-Squares (IRLS) algorithm. Because the separation process removes the source signatures to yield an impulsive model, the separated data are convolved with a desired output wavelet. Here, they are convolved with a Ricker wavelet ($f_c = 50$ Hz) to be comparable to the input data. Figures 2.5a and b show the source 1 and source 2 data after separation. The differences between the reconstructed and the true single source data are shown in Figures 2.5c and d. It is apparent that the separation was not successful. To assess the separation, we calculate the root-mean-square (RMS) error as the RMS of the difference between the separated data, $d_{sep}$, and the true reference data, $d_{ref}$, normalized by the RMS of the reference solution, according to:

$$\text{RMS error} = \sqrt{\frac{\sum (d_{sep} - d_{ref})^2}{\sum (d_{ref})^2}}. \quad (2.26)$$

The RMS errors for the separated source 1 data and source 2 data are 67% and 68% respectively, and remaining crosstalk of the simultaneous source can be identified in the reconstructed data. The spectra of the true and the reconstructed data (Figures 2.5e and f) also confirm that the single-frequency method fails to separate
Figure 2.3: Encoding Sequences: (a,b) Bipolar Kasami sequences, (c,d) After convolution with Ricker wavelet ($f_c = 50$ Hz), (e,f) autocorrelations, (g) crosscorrelation.
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**Figure 2.4:** 500 m Common offset data of the area of interest: (a) Source 1 encoded with sequence 1, (b) Dithered source 2 encoded with sequence 2 shown in source 1 firing time, (c) Dithered sequence encoded sim-source data in source 1 firing time.

The sim-source data with such a source sampling and that the amplitudes of the events cannot be recovered correctly.

The dithered, sequence-encoded data (Figure 2.4c) were also separated using the single-frequency approach with an IRLS algorithm on windows of 10 data traces. The separated data are shown in Figures 2.6a) and b). The encoding sequences are removed during the separation and the impulsive output data are convolved with a Ricker wavelet \( f_c = 50 \) Hz and compared to the true single source data (Figures 2.6c and d). The single-frequency method also fails to separate the sequence-encoded data. Artefacts from the simultaneous source and of the encoding sequences are clearly visible in the separated data and the difference plots. The true amplitudes of the events cannot be reconstructed. Figures 2.6e) and f) show the amplitude spectra of the original and the reconstructed data, which retain the notches of the encoding sequences. Since the sequences are not changed between shots, the notches within the sequences cannot be filled by the single-frequency method and the RMS errors of the separated data are even higher than for the dithered data. The separation results presented in Figures 2.5 and 2.6 are a good evidence that the single-frequency method is not capable to separate sim-source data with shot spacings of 40 m given the complexity of the data and an alias factor of 2 at the Nyquist frequency of 125 Hz.
2.3 Synthetic Data Study

Figure 2.5: Sim-source separation of dithered data with single-frequency method: (a) separated source 1 data, (b) separated source 2 data, (c) difference between original source 1 data and reconstructed source 1 data, (d) difference between original source 2 data and reconstructed source 2 data, (e) spectra of original and reconstructed source 1 data, (f) spectra of original and reconstructed source 2 data.
Figure 2.6: Sim-source separation of dithered, sequence-encoded data with single-frequency method: (a) separated source 1 data, (b) separated source 2 data, (c) difference between original source 1 data and reconstructed source 1 data, (d) difference between original source 2 data and reconstructed source 2 data, (e) spectra of original and reconstructed source 1 data, (f) spectra of original and reconstructed source 2 data.
2.3.2 Separation with a multifrequency method

In a next step, we have employed the multifrequency method for source separation. Again, the data (50 traces) are subdivided into windows of 10 traces and processed individually with the approach discussed in the methodology section, solving for the strongest components at a number of iterations. Here, we choose 0.01% of the strongest components for each source at each iteration and iterate on the residual. For the following separation examples, a maximum of $L = 80$ neighboring frequency components on either side of the central frequency with a frequency sampling of $df = 0.5$ Hz were used in the separation method with 60 iterations.

The separation results for the dithered sources are presented in Figure 2.7a and b. The difference plots between the true sources and the reconstructed data are shown in Figures 2.7c and d and have an RMS error of approximately 28%. This is a reasonable separation result considering the order of aliasing present in the data (Figure 2.2c). Small crosstalk artefacts of the simultaneous source are still visible, but the amplitudes are better recovered than for the single-frequency method. This is also confirmed by the comparison of the spectra of the true and reconstructed single-source data (Figures 2.7e and f).

The separation results for the dithered, sequence-encoded sim-source data with the multifrequency method is shown in Figure 2.8. Using the same parameters as before, there is a significant uplift in the source separation compared to the conventional dithered sim-source separation (Figure 2.7). The RMS error is down to 14% for source 1 and to 11% for source 2. This is also confirmed by the spectra of the true and the reconstructed single-source data, which show only minor discrepancies. The multifrequency method fills the notches of the sequences and allows to exploit the orthogonality of the encoding sequences. The comparison of these results clearly shows the benefit of using dithered, sequence-encoded sim-source data for source separation over conventionally dithered sim-source data.

2.4 Discussion

The presented examples demonstrate the benefit of using sequence encoding for sim-source separation in combination with dithering. The comparison of the single-frequency method with the multifrequency method showed that the orthogonality of the sequences can be exploited by the multifrequency algorithm. By adapting the multifrequency method by Ji et al. (2012, 2013), synthetic Common Offset data with a shot spacing of 40 m were successfully separated. The combination of multiple frequency components in the separation method solution has numerous advantages.
Figure 2.7: Sim-source separation of dithered data with multifrequency method: (a) separated source 1 data, (b) separated source 2 data, (c) difference between original source 1 data and reconstructed source 1 data, (d) difference between original source 2 data and reconstructed source 2 data, (e) spectra of original and reconstructed source 1 data, (f) spectra of original and reconstructed source 2 data.
2.4 Discussion

Figure 2.8: Sim-source separation of dithered, sequence-encoded data with multi-frequency method: (a) separated source 1 data, (b) separated source 2 data, (c) difference between original source 1 data and reconstructed source 1 data, (d) difference between original source 2 data and reconstructed source 2 data, (e) spectra of original and reconstructed source 1 data, (f) spectra of original and reconstructed source 2 data.
The method enables separating spatially aliased signal by linking the phase of the model components across several frequencies, which proves to be crucial when dealing with common offset data and realistic shot spacings. More importantly, it takes advantage of the orthogonality of the encoding sequences to enhance the source separation making it superior to source dithering only. Furthermore, the spreading of the source signal through time introduces notches in the spectra of the encoding sequences. When the same sequences are used for all shots, these zeros in the spectra can be filled with the multifrequency method by means of combining multiple frequency components in the algorithm. Abma and Ross (2013) proposed to overcome the problem of spectral notches by varying the sequence from shot to shot and used several patterns of sequences that do not share the same spectral zeros. The notches can then be reconstructed by the signal from nearby traces. For the case of sim-source separation with the multifrequency method, using a different set of sequences for each shot could potentially offer an even further uplift for the spectral reconstruction.

In the multifrequency method, the set of basis functions can be very large making the inversion of the system of equations for source separation computationally expensive; therefore, a sufficiently fast sparse inversion algorithm is required. By solving at each iteration only for a small fraction of the strongest components of the $\tau - p$ model, only a small set of basis functions is considered that can be inverted. A further reduction of the computational cost of the multifrequency solver would still be desirable and also be beneficial to implement a full time-domain algorithm. The demonstrated examples with neighboring frequency components in a range of up to 40 Hz on either side of the central frequency are already close to a time-domain solution, but a full time-domain solution could even further enhance the separation of sequence-encoded sim-source data.

The bipolar nature of the employed set of sequences and the feasibility of adapting the discussed sequences to air-gun arrays requires further research. To what extent these sequences can be reproduced by an air-gun array is debatable; however, by using a simulated annealing approach Halliday et al. (2012) showed that air-gun firing sequences can be designed and optimized for optimal auto- and crosscorrelation properties. This is achieved by minimizing the peak amplitude of the deconvolution of one sequence by the other, assuming a high signal-to-noise ratio. Increasing the sequence length and including a large number of air-gun sources could further improve the separation properties of the orthogonal sequences sets, although the sequence length may be restricted by the listening time and short sequences could still give could separation results for some applications. Optimal orthogonal sequences could allow sim-source separation simply by correlation and could potentially lead
2.5 Conclusion

We have demonstrated that source sequence encoding can be used to improve simultaneous source separation when used in combination with time dithering. Our synthetic examples show that the source separation with sequence encoding outperforms the source separation with source dithering only. This uplift in source separation was achieved using encoded air-gun arrays by firing sub-elements of an air-gun array individually and separating the sim-source data with a multifrequency method. The source sequences are chosen to be close to orthogonal to each other and are separated using a coherency-based approach. The multifrequency method enables exploitation of the orthogonality of the sequences in the separation method.
Furthermore, it enables dealing with large shot spacings, as we demonstrated in our synthetic examples with 40 m source spacing.

For these examples, a set of optimized Kasami sequences were used that are convolved with a source signature. For sim-source data acquisition with conventional marine air-gun sources, air-gun firing sequences can be optimized with respect to their auto- and crosscorrelation properties. The current paper demonstrates the significant uplift that could be realized if these source-related practical aspects are addressed. The multifrequency method is computationally expensive, but optimization towards a full time-domain solution may further improve the separation of sequence-encoded data, although it assumes an amplitude response of the subsurface that is smooth across all frequencies, which might not be given for real data. Further analysis of the choice of source sequences and the optimization of the algorithm to solve the inverse problem are all topics of ongoing research.

The use of encoded source sequences is also key for the acquisition of source-gradient data, because additional simultaneous sources could be included with constraints of time-dithering. This will enable application of source-gradient techniques for source-side deghosting and source-side reconstruction as well as the use of novel full-wavefield vector acoustic imaging techniques.

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### References


Chapter 3

Optimizing near-orthogonal air-gun firing sequences for marine simultaneous source separation

Abstract

Air-gun arrays can be encoded by firing individual air guns sequentially over a range of time. This marine source encoding is shown to be particularly beneficial for simultaneous source separation, which can exploit the orthogonality of the encoding sequences to improve the source separation. We have developed a method to design encoding sequences for air-gun arrays having minimized crosscorrelation and optimized autocorrelation properties. By varying the firing times of the individual air-gun subelements, different encoding sequences are constructed using a simulated annealing approach so that their orthogonality properties are optimized. These optimized sequences are then used for time-dithered simultaneous source encoding. Realistic synthetic data examples show a significant improvement of simultaneous source separation. We also demonstrate the robustness of the method for take-off angle variations and possible errors in sequence estimation.

3 Optimizing near-orthogonal air-gun sequence for simultaneous source separation

3.1 Introduction

The concept of tuning an air-gun array to generate a sharp source signal has recently been challenged by new developments in marine seismic acquisition. Rather than activating all air guns at nearly the same time as during conventional acquisition, the subelements can also be fired independently over a period of time. This sequence shooting encodes the source signature yielding a sequence of impulses with reduced peak amplitude. The idea of firing the air-gun array sequentially is not new: it was originally discussed by Stoffa and Ziolkowski (1983) as a method to decompose the seismic source array. Ziolkowski (1984) then introduced the term “machine gun” array. However, the limited computational resources available at that time did not allow computationally expensive sparse inversion algorithms to be applied, which may help to explain why this sequential firing method was not followed up for seismic acquisition at that time. Recently, Abma and Ross (2013) proposed to detune an air-gun array to reduce peak amplitudes for minimal environmental disturbance. A sparse inversion method enables to recover the geophysical data from this “Popcorn shooting” method as would have been obtained from an impulsive source.

A new application of this sequence shooting for marine acquisition was discussed by Robertsson et al. (2008), who proposed to choose the sequences to be close to orthogonal to each other. These near-orthogonal sequences have minimized cross-correlation and optimal autocorrelation properties (maximized peak-to-side-lobe ratios). Mueller et al. (2015) demonstrated that this orthogonality of the sequences can be used as an additional feature for simultaneous source separation. Using a multifrequency algorithm, they exploited the sequence orthogonality and showed that source sequence encoding can significantly improve simultaneous source separation compared to using time dithering only. Because most simultaneous source separation or deblending algorithms are applied in domains that constitute multiple simultaneous source shots (for instance, common offset gathers or common receiver gathers), they require a dense source sampling or the application of computationally expensive algorithms that can deal with spatially aliased data (Mueller et al., 2015). Wu et al. (2015) discussed an alternative approach, called shot repetition, which activates a broadband source more than once at the same location. The activation times of these two simultaneous sources are coded with near-orthogonal sequences, similar to Mueller et al. (2015), and the separation is performed in common shot gathers.

In land seismic acquisition, the concept of orthogonality has long been known and pseudorandom sweeps are often used in Vibroseis surveys for simultaneous source acquisition. Dean (2014) provided a thorough overview of how pseudorandom sweeps
can be designed for Vibroseis acquisition. The fundamental advantage of land seismic acquisition over conventional marine seismic acquisition is the availability of a fixed, stationary source for each shot location and the full control of the frequency output of the Vibroseis source, which enables generating well-controlled sweeps over longer periods of time. Marine seismic acquisition is still limited to the use of air guns, which do not allow the emission of sweeps but only the firing of individual air-gun pops. On the other hand, land seismic acquisition is often limited by severe coupling issues and non-linear effects. These limitations restrict the shot repeatability of Vibroseis shooting and near-surface variations can lead to significant source signature variations for different shot locations. In marine seismic acquisition, there are no coupling issues and the repeatability of shots and air-gun signatures are generally well-controlled. Although research is conducted on marine vibrator technology (Pramik et al., 2015), the sound pressure level generated by current marine Vibroseis sources is significantly lower than for seismic air guns, which still prevents their use for the acquisition of conventional marine seismic data.

When sequence encoding or Popcorn sources are used in single-shooting mode, random sequence patterns are used for each shot position. This randomness of the source sequences is important to accurately reconstruct the desired signal, because it also randomizes any errors in the reconstruction process (Abma and Ross, 2015). When sequence encoding is used to enhance simultaneous source separation, choosing random sequences is not always sufficient, as the encoding sequences must be close to orthogonal to each other to improve the separation. Although purely random sequences have good orthogonality properties, they only exhibit these properties on average or for infinitely long sequences. When a small number of short sequences are used repeatedly, it is better to design sequences that guarantee orthogonality. Encoding sequences can be designed and optimized with respect to their orthogonality properties to have these desired properties. Halliday et al. (2012) discuss the optimization of two sequences using a simulated annealing approach that minimizes the maximum value of the deconvolution of one sequence by the other. Mueller et al. (2015) used a set of optimized Kasami sequences (Fan and Darnell, 1996; Dean, 2014) that are transformed into bipolar sequences and convolved with a Ricker wavelet to demonstrate the full benefit of sequence encoding for simultaneous source separation.

Here, we demonstrate how near-orthogonal air-gun sequences can be designed with a simulated annealing approach. In our optimization method we vary the firing times of individual air-gun signatures to generate a pair of encoding sequences having minimized crosscorrelation and optimized autocorrelation. We show that a set of optimized sequences can be used for simultaneous source separation with the method introduced by Mueller et al. (2015) and test the robustness of the method.
for its dependence on take-off angle and sequence estimation errors.

3.2 Method

There is considerable literature on the concept of sequence orthogonality for binary sequences, which are widely used in system communications (Fan and Darnell (1996) and Golomb and Gong (2005) and references therein). For binary sequences \{0, 1\} or \{+1 and −1\} Welch (1974) has established lower bounds on how small the crosscorrelation and autocorrelation can simultaneously be. With respect to this Welch bound, the small set of Kasami sequences is an optimal collection of binary sequences (Fan and Darnell, 1996). This also motivated Mueller et al. (2015) to use sequences generated by the convolution of Kasami sequences with a bandlimited wavelet to demonstrate the benefit of orthogonality for simultaneous source separation. Optical orthogonal codes are another family of \{0, 1\} sequences with good auto- and crosscorrelation properties that are frequently used in system communications (Chung et al., 1989; Fan and Darnell, 1996).

When air-gun sequences are considered, which consist of firing individual air guns over a range of time, the definition of such lower bounds is more difficult. Air-gun signatures are broadband pulses that are modulated by the bubble oscillations. The autocorrelation peak of these sequences is not limited to zero lag, as is the case for binary sequences, but has a certain width. This band limitation of the signal also influences the shape and appearance of the sidelobes. Because the auto- and crosscorrelation properties of orthogonal binary sequences cannot be achieved with air-gun sequences whose construction is limited by the air-gun signature bandwidth, optimized air-gun sequences are often referred to as close-to-orthogonal or near-orthogonal. These air-gun sequences are more complex than binary sequences, as they are made up of different wavelets with different spectral content and initiation time. The possible parameter space is extremely large, particularly as we always consider a combination of two or more sequences, and there is no theory that defines an analytic generation of near-orthogonal air-gun sequences. Therefore, we choose an approach that generates a vast number of different air-gun sequences and retain the set with the best orthogonality properties.

3.2.1 Optimization by simulated annealing

For near-orthogonal air-gun sequences, there are two essential parameters that determine the quality of the orthogonality properties and that can be varied for their optimization. Assuming that a certain number of air guns can be fired over a limited
3.2 Method

range of time, these are the air-gun signature and the firing time. The signature of an air gun depends on the employed gun type and the firing depth, which determines the characteristic bubble time period. This means that to design near-orthogonal air-gun sequences, we can vary the air-gun signatures and firing times until we obtain a set of sequences with the desired orthogonality properties. Here, we choose an approach based on simulated annealing (Kirkpatrick et al., 1983). The optimization method minimizes a cost function that describes the orthogonality properties and computes new sequence realizations until the cost function converges to a minimum. At each iteration one of the sequence defining parameters is changed. We assume that for each air-gun sequence, \( s \), we can fire a certain number of air guns, \( g \). Mathematically this minimization can be expressed as:

\[
\text{minimize} \quad E_{\text{cost}} (t^s_g, W^s_g) \\
\text{subject to} \quad 0 \leq t^s_g \leq T_{\text{max}} \\
\text{and} \quad W^s_g \in W_{\text{sig}},
\]

where \( E_{\text{cost}} \) is the chosen cost function that is minimized. \( t^s_g \) is the firing time of the individual air guns constituting the respective sequence, \( s \). \( W^s_g \) is the signature of each of these air guns and can be chosen from the family of possible air-gun signatures \( W_{\text{sig}} \).

To optimize the near-orthogonal air-gun sequences, we define a cost function that evaluates crosscorrelation and autocorrelation properties of the sequences. For simplicity, the optimization approach is described here for two sequences, although it can be extended for the optimization of multiple sequences. In the case of two sequences, \( S_1 \) and \( S_2 \), the cost function for the minimization approach described by equation 3.1 is defined as:

\[
E = \gamma \cdot CC + (1 - \gamma) \cdot (AC_1 + AC_2), \quad 0 \leq \gamma \leq 1,
\]

where \( CC \) is the term that evaluates the crosscorrelation properties of the two sequences, and \( AC_1 \) and \( AC_2 \) are terms that evaluate the autocorrelation properties of \( S_1 \) and \( S_2 \). The weighting factor \( \gamma \) determines which term is most relevant for the optimization. Here, the primary optimization target is the minimization of the crosscorrelation term and thus \( \gamma > 0.5 \) is chosen. The crosscorrelation of two finite sequences, \( S_1 = \{s_i\} \) and \( S_2 = \{t_i\} \) of length \( n \), defined for \( 1 \leq i \leq n \), is given by (Golomb and Gong, 2005):

\[
R^C_{S_1,S_2}(\tau) = \frac{\sum_{i=1}^{n-\tau} s_i t_{i+\tau}}{\sqrt{\sum_{i=1}^{n} |s_i|^2} \sqrt{\sum_{i=1}^{n} |t_i|^2}}.
\]
With this definition of the normalized crosscorrelation, we define the crosscorrelation minimization term, \( CC \), in equation 3.2 as:

\[
CC = \max \left( \sqrt{\left( R^C_{S_1,S_2}(\tau) \right)^2} + \beta \cdot \frac{\sqrt{\sum_{\tau}^M \left( R^C_{S_1,S_2}(\tau) \right)^2}}{M} \right),
\]

where the first term accounts for minimizing the absolute peak of the crosscorrelation and the second term minimizes the normalized L2-norm of the crosscorrelation, i.e. its energy, with \( M \) being the length of the crosscorrelation and \( \beta \) a weighting factor. We choose \( \beta = 1 \) for our optimization examples.

As a secondary design criterion, we try to optimize the sharpness of the autocorrelation peaks and minimize its peak-to-sidelobe ratios. The normalized autocorrelation of a sequence, \( S \), is given by:

\[
R^A_S(\tau) = \frac{\sum_{i=1}^{n-\tau} s_is_{i+\tau}}{\sum_{i=1}^{n} |s_i|^2}. \tag{3.5}
\]

With this definition the autocorrelation minimization terms \( AC_s, s = 1, 2 \), are defined as:

\[
AC_s = \frac{\sqrt{\sum_{\tau \leq \tau_{\text{off}}}^\tau \left( R^A_S(\tau) \right)^2}}{\tau_{\text{off}}} + \mu \cdot \max \left( \sqrt{R^A_S(\tau)^2} \right)_{\tau > \tau_{\text{off}}}, \quad \tau \geq 0, \tag{3.6}
\]

where the first term minimizes the L2-norm in a window around the central peak. The width of this window, defined as \( 2 \cdot \tau_{\text{off}} \), depends on the dominant frequency content of the sequences and \( \tau_{\text{off}} \) is typically chosen as:

\[
\tau_{\text{off}} \approx \frac{2}{f_d}, \tag{3.7}
\]

with \( f_d \) the dominant frequency of the air-gun sequences. The minimization of this term yields a sharp autocorrelation peak. The second term in equation 3.6 with the weighting factor \( \mu \) minimizes the peak-to-sidelobe ratio of the autocorrelation.

Depending on the algorithm used to exploit the orthogonality (i.e. the separation algorithm), different features of the autocorrelation are relevant. Most often the peak-to-sidelobe ratio is the most important criterion (\( \mu > 1 \)). However, for sparse inversion algorithms, which only solve for the strongest components at each iteration, the sharpness of the autocorrelation peak can also be critical.
3.3 Sequence Optimization Examples

To design near-orthogonal air-gun sequences, we use a set of six different air guns of varying size that are typical for conventional air-gun arrays. The notional signatures for these air guns fired at different depths were modelled and then convolved with the source ghost functions for the respective firing depths. The modelled near-field air-gun signatures were filtered with a 120 Hz high-cut filter and extrapolated to a receiver depth of 1000 m. Figure 3.1 shows the resulting far-field signatures for the six different air guns modelled for a source at a depth of 6 m.

**Figure 3.1:** Six air-gun signatures estimated from notional sources for a source depth of 6 m, extrapolated to a receiver depth of 1000 m and filtered with a 120 Hz high-cut filter. Note that the bubble pulses of the air guns vary with the air-gun volume and that these signatures do include the free-surface source ghost for vertical take-off angle.
The source ghost has opposite polarity to the primary wavelet and is delayed in time (Parkes and Hatton, 1986):

\[ t_{\text{delay}} = \frac{2z_s \cos(\phi)}{c_w}, \]  

(3.8)

with \( z_s \) the firing depth, \( \phi \) the take-off angle to the vertical and \( c_w \) the sound velocity of water. Besides the primary pulse and its free-surface ghost, the air-gun signatures include the signal of the oscillating bubble, which expands and contracts multiple times before it dissolves or breaks the surface. Its oscillation period depends on the firing pressure, the air-gun volume and the source depth (Parkes and Hatton, 1986). The dependence of the bubble period on the air-gun volume is also visible for the signatures shown in Figure 3.1. Because of the source ghost and the bubble effect, the air-gun signatures include signal with significant positive and negative amplitude. This fact can be exploited to generate near-orthogonal air-gun sequences. When air-gun sequences are crosscorrelated, the positive values of one sequence interferes destructively with the negative values of the other sequence and vice-versa. Thus, to design near-orthogonal sequences, the existence of the source ghost and bubble effects can benefit the orthogonality properties.

To design a near-orthogonal air-gun sequence pair, we consider the case of a fixed source depth of 6 m as representative for conventional marine seismic acquisition. We assume that one air-gun source array consists of three subarrays with six different air-gun signatures as shown in Figure 3.1 and that each air gun can be fired once. Here, we use a time sampling of \( dt = 4 \text{ ms} \) for the signatures. We start the optimization by computing a set of random sequences, for which each of the 18 air guns is fired exactly once during a period of 1 second with a random firing time drawn from a uniform distribution. Figures 3.2a and 3.2b show the two random sequences that serve as starting sequences for our optimization. Both autocorrelations show sidelobe energy (Figure 3.2c and 3.2d), with the sidelobe peak in the normalized autocorrelation of Sequence 2 (0.239) being slightly higher than for Sequence 1 (0.151). Their normalized crosscorrelation has an absolute peak value of 0.313.

To start the optimization procedure, we compute the cost function describing the orthogonality properties of these starting sequences (according to equation 3.2). In a next step, the optimization algorithm chooses a random air gun and draws a new random firing time for it in the specified firing range of 0 to 1 s. Then the cost function of this new sequence set is computed and the new firing time for the air-gun source is accepted if the cost function is reduced or if the increase of the cost function falls within the accepted range of the simulated annealing algorithm. When the cost function is not reduced for a certain number of iterations, the optimization algorithm...
3.3 Sequence Optimization Examples

Figure 3.2: (a,b) Two sequences of 18 air guns, each fired exactly once during a period of 1 second with random firing times drawn from a uniform distribution. (c,d) Autocorrelations of a and b. (e,g) Spectra of the two sequences. (f) Crosscorrelation of a and b.

is stopped and the obtained sequence set is retained. Figure 3.4a and 3.4b show the set of optimized sequences obtained after several thousand iterations (Figure 3.3). The sidelobe energy of both autocorrelations has been significantly reduced (sidelobe maxima: 0.118 for Sequence 1 and 0.100 for Sequence 2), as shown by Figure 3.4c and 3.4d. The absolute crosscorrelation peak has also been substantially lowered to 0.120 (Figure 3.4f). We will demonstrate subsequently that this new set of optimized
3 Optimizing near-orthogonal air-gun sequence for simultaneous source separation

![Minimization of cost function](image)

**Figure 3.3:** Minimization of cost function for the first 1000 iterations, which each includes a large number of evaluated perturbations of possible firing time combinations. After each iteration, the acceptance criterion of the simulated annealing algorithm is lowered. During the initial iterations possible increases of the cost function are still accepted. With increasing number of iterations, the cost function slowly converges to a local minimum.

near-orthogonal sequences has considerable benefits for applications that exploit the sequence orthogonality.

### 3.4 Simultaneous source separation with designed air-gun sequences

To demonstrate the benefit of optimized near-orthogonal air-gun sequences, we consider the simultaneous source separation application by Mueller et al. (2015). There, we demonstrated how simultaneous source separation can be substantially improved when encoded source sequences are used in combination with time dithering and a multifrequency algorithm. The multifrequency method, described in detail by Ji et al. (2013), is key to exploiting the sequence orthogonality. Here, we test this source separation using the random set of air-gun sequences shown in Figure 3.2 and compare its performance to the separation results of the optimized near-orthogonal
3.4 Simultaneous source separation with designed air-gun sequences

Figure 3.4: (a,b) Two sequences of 18 air guns, designed using a simulated annealing approach that optimizes the orthogonality properties. (c,d) Autocorrelations of a and b. (e,g) Spectra of the two sequences. (f) Crosscorrelation of a and b.

sequence set shown in Figure 3.4. Following the synthetic data generation by Mueller et al. (2015), we generate synthetic shot records of a North Sea model (Figure 3.5a) for sources at a depth of 6 m and receivers at a depth of 20 m with a finite-difference code without a free surface. The time sampling is $\Delta T = 4$ ms and the data are sorted into common offset gathers with a source spacing of 40 m, with the position of the second source chosen in-between the shot positions for Source 1 (i.e., at a 20 m
offset position). The data are windowed on a focus area indicated in Figure 3.5a containing the major structure with three tilted fault blocks and a flat spot in the central fault block. The sequence encoding of the sources is achieved by using the respective sequences as source encoding signatures for Sources 1 and 2. It is important to note that we do not account for the air-gun array aperture and the motion of the array during the sequence firing, but that we assume a stationary monopole source. The synthetic simultaneous source data are generated by addition of the shot record for Source 1 and the shot record of Source 2 (from a position offset of 20 m) with a time shift corresponding to the time dithering. The shots of Source 2 are dithered with a random time delay of +100 to +500 ms drawn from a uniform distribution. The same dithers are applied for the two cases of random and optimized sequence encoding. Figure 3.5b shows the dithered, sequence-encoded simultaneous source data generated with the set of optimized sequences (Figure 3.4).

To separate the simultaneous source data, we subdivide the data (50 traces) into windows of 10 traces and process these windows individually using the multifrequency separation method by Mueller et al. (2015). We solve for 0.01% of the strongest components for each source at each iteration and iterate on the residual (60 iterations). Here, a maximum of $L = 80$ neighboring frequency components are used on either side of the central frequency with a frequency sampling of $df = 0.5$ Hz. The separation results for the random sequence encoding and the optimized sequence encoding for Source 1 are presented in Figures 3.5c and 3.5e, respectively. The difference plots between the true sources and the reconstructed data are shown in Figures 3.5e and 3.5f. To estimate the quality of the separation results, we calculate the root-mean-square (rms) error as the rms of the difference between the separated data, $d_{sep}$, and the true reference data, $d_{ref}$, normalized by the rms of the reference solution, as given by Mueller et al. (2015). In the case of the random-sequence encoding, the rms error of the separated sources is 16% for Source 1 and 15% for Source 2. Using the set of optimized sequences, the rms error of the separated sources is reduced to 9% for Source 1 and 8% for Source 2. This clearly shows that the separation algorithm benefits from the optimization of near-orthogonal air-gun sequences. It is also important to note that both separation examples outperform the simultaneous source separation with a dithered, tuned air gun, for which the corresponding rms errors of the separated Sources 1 and 2 are 28% (Mueller et al., 2015). The separation errors are also lower than the ones obtained for the separation with the bandlimited Kasami sequences. This might be due to the fact that the total length of the designed air-gun sequences is longer than the sequences used for the encoding by Mueller et al. (2015). These separation errors were obtained with a parametrization that was as close as possible as for the sequence separation
presented in this paper (same number of iterations, same percentage of strongest components, and so forth) and given the complexity of the data and the same shot spacing of 40 m, we expect an alias factor of 2 at the Nyquist frequency of 125 Hz, which poses severe challenges in terms of spatial aliasing.

3.5 Sensitivity Study

The observed benefits of the designed near-orthogonal air-gun sequences in the previous separation examples are promising, yet it is crucial to demonstrate the robustness of the method. Therefore we investigated a number of practical effects that can limit the benefits of sequence encoding for simultaneous source separation. In this analysis, we do not investigate and account for other limiting effects such as noise or the radiation pattern of the air-gun array, which spread signal over time and space. This sensitivity study was performed under the assumption of stationary sources and a noise-free environment. We do also not account for the effective array aperture due to the distance the boat moves during the sequence duration.

The simultaneous source separation method assumes that the encoding sequences are known. Although the firing times of the individual air guns can be controlled, practical aspects or weather conditions can lead to deviations of the actually fired sequence from the theoretically intended one. With the near-field hydrophones available for modern air-gun arrays possible deviations can be recorded and thus a better estimate of the transmitted sequences can be used in the separation algorithm. Even though the near-field hydrophones provide very good control of the true firing times, possible amplitude variations can still occur even when near-field measurements are available.

To evaluate the effect of amplitude variations, we conducted the simultaneous source separation for the previous examples shown in Figures 3.5 for the set of optimized sequences (Figure 3.5c and 3.5e). The designed set of optimized sequences (Figure 3.4) was assumed as input to the separation algorithm, but the sequences used to encode the simultaneous source data were modified by amplitude variations of the individual air guns. In a first test, the amplitudes of the individual air-gun signatures were systematically perturbed with random variations of $\pm 10\%$ drawn from a uniform distribution for each air gun. This caused an increase of the mean rms error for Source 1 and 2 from 9\% to 14\%. A second test with systematic random amplitude variations of $\pm 20\%$ drawn from a uniform distribution for each air gun resulted in a further increase of the rms error to 19\%. Although we do not expect that amplitude variations up to 20\% remain unnoticed, the separation results still
3 Optimizing near-orthogonal air-gun sequence for simultaneous source separation

- **a) Gullfaks Velocity Model**
- **b) Sim-source data (Opt. Seqs)**
- **c) Separated Source 1 - Optimized Seqs.**
- **d) Separated Source 1 - Random Seq**
- **e) Error of Source 1 (c): rms error: 9%**
- **f) Error of Source 1 (d): rms error: 16%**
outperform the separation result for the dithered, conventional tuned air-gun sources (rms error of 28%).

A further scenario is the failure of a gun to fire. Although this would be noticed by the near-field hydrophones and thus the actual sequences could be used for the separation algorithm, we tested the influence of missing guns. We assumed that for each source one of the 18 air guns failed to fire and that this malfunction remained unnoticed. The corresponding separation results showed an increase of the separation error from 9% to 24%. So even in this unlikely case of an unnoticed failure of two air guns for one shot, the separation still surpasses the reference case for the separation with dithered, tuned air-gun sources (rms error of 28%). It is again important to note that for reasons of comparability the same parametrization was used in all separation examples, which are summarized in Table 3.1. An adaptation of the parametrization for each individual case could potentially reduce the separation error. The significant increase of the rms error from 9% to 24% in the case of an unnoticed gun failure is an important reason why the actual signatures should be recorded.

In a next step, we evaluated the influence of the take-off angle on the separation results. The separation results in Figure 3.5 assume vertical take-off from the stationary centre of the source array and thus constant delay times for the source ghosts of the individual air guns. However with increasing take-off angle the delay times of the source ghosts decrease according to equation 3.8. The dependence of the occurrence of the source ghost on take-off angle and source depth is illustrated in Figure 3.6. The variations are larger for deeper sources and the effect is less severe.
Table 3.1: Summary of the simultaneous source separation results with the modified sequences and the corresponding mean rms error of the two sources, S1 and S2.

<table>
<thead>
<tr>
<th>Sequence Modification</th>
<th>mean rms error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct sequences (no modifications)</td>
<td>9%</td>
</tr>
<tr>
<td>Systematic random amplitude variations of ±10%</td>
<td>14%</td>
</tr>
<tr>
<td>Systematic random amplitude variations of ±20%</td>
<td>19%</td>
</tr>
<tr>
<td>Failure of 1 gun for each source</td>
<td>24%</td>
</tr>
<tr>
<td>Simultaneous source separation with dithered, tuned air-gun array</td>
<td>28%</td>
</tr>
</tbody>
</table>

for take-off angles below 40°, which represent most of the useful reflected signal in conventional seismic data acquisition.

To test the robustness of the method for different take-off angles, we computed the transmitted sequences for different take-off angles up to 40° and used those to generate the sequence-encoded simultaneous source data. For the simultaneous source separation we used the sequences for vertical take-off angle (Figure 3.4). Figure 3.7 shows the mean of the rms error for both sources in dependence of the take-off angle. Up to take-off angles of 30° the rms error is smaller than the 28% observed for the reference case of the separation with the dithered, tuned air-gun sources. Only for take-off angles above 30° the separation performance drops below this reference value.

Instead of assuming the sequences for vertical take-off angle, we can also use the transmitted sequences for a different take-off angle in the simultaneous source separation. To demonstrate this, we performed the separation for the different take-off angles with the transmitted encoding sequences for a take-off angle of 20°. Figure 3.7 shows that although this results in a small increase of the rms error for smaller take-off angles, it stabilizes the separation for higher take-off angles. These results suggest that the method is stable in terms of take-off angle variations.
3.6 Discussion

The presented examples demonstrate that air-gun sequences can be designed to be near-orthogonal. Although random air-gun sequences typically produce acceptable orthogonality properties, optimized firing sequences with improved orthogonality properties provide significant benefits for applications that exploit the sequence orthogonality, in particular those that rely on few and relatively short sequences. One of these applications is simultaneous source separation for marine seismic acquisition, where sequence encoding is used to enhance the separation results (Wu et al., 2015; Mueller et al., 2015). Using an optimized set of air-gun sequences, we achieved a substantial uplift in the source separation of sequence-encoded sources and the rms error was reduced from 16% to 9%. For simultaneous source separation algorithms that are based on sparse inversion, not only the crosscorrelation peaks are critical to suppress crosstalk, but also the sharpness of the autocorrelation peak at zero

Figure 3.6: Source ghost delays in dependence of source depth and take-off angle.
lag is essential for good separation results. This is accounted for by the term in the cost function definition, which minimizes the energy in a window around the autocorrelation peak. The design criteria and weighting factors in the cost function require adaptation depending on the sensitivity of the application and the algorithm used to exploit the sequence orthogonality on the different orthogonality properties. The algorithm presented here can also be used to generate a whole set of orthogonal sequences, which allows us to change the firing sequences from shot to shot, making time dithering for simultaneous source separation redundant. The optimization of more than two near-orthogonal air-gun sequences could also enable the acquisition of more than two simultaneous sources.
A possible limitation of sequence encoding an air-gun array is the reduction of the peak amplitude of the source signal (Hopperstad et al., 2014). For which acquisition scenarios this can cause a signal-to-noise problem or how subsequent data processing can mitigate this reduction of emitted energy requires further investigation. Although Abma and Ross (2015) argued that the primary’s amplitude after reconstruction is preserved despite the reduction in total acoustic energy, it is not completely clear how the signal-to-noise ratio is affected.

The reconstruction of conventional air-gun signatures from using air-gun firing sequences or the successful simultaneous source separation of sequence-encoded data is sensitive to the accuracy of the firing sequence estimates. Particularly, in rough sea conditions with reduced reflection coefficients for the source ghost and possible variations of the source time delay, it may be critical to have near-field air-gun measurements to correct the firing times and to estimate adequate far-field firing signatures. Abma and Ross (2015) argued that, if firing signature estimates differ too much from the real signatures, modifications of the coherency threshold (i.e., the parametrization of the reconstruction or separation algorithms) can be made to limit the impact of these estimation errors on the reconstruction results. In the examples shown here, we used the same parametrization for all separation results. However, the adaptation of the separation parameters for the individual examples in the sensitivity study (coherency threshold, number of iteration, and others) could potentially improve the separation results for the cases with sequence estimation errors.

An important aspect of sequence firing is the spreading of energy in space due to the source motion. Particularly for longer sequences, this should be taken into account and likely requires correction. However, we argue that with relatively short sequences of 1 s duration, for which source movement is small compared with the typical wavelengths of the spectrum emitted by air guns, near-orthogonal sequence sets can be obtained and no significant increase in listening time is required. In a next step, continuous firing sequences could be designed that consist of individual strings being orthogonal to each other and allowing the acquisition from one self-simultaneous source, so that the recorded data overlaps itself.

Critical for all designs of firing sequences is the dependence of their far-field signatures on the take-off angle. Because the take-off angle also has an effect on the occurrence of the source ghost, all applications involving sequence firing of marine seismic sources must be proven stable for near-vertical take-off angles. The synthetic data results of the take-off angle variations considered in our sensitivity study suggest that the separation results are stable in these cases in certain conditions. Our analysis did not account for the spatial aperture of the source array, although this
has a significant impact on the radiation pattern causing a potentially strong angular dependence. The simultaneous source separation examples with sequence encoding presented here outperforms the separation with dithered, tuned air-gun sources up to take-off angles of 30° and higher. The more severe implications of this effect for larger take-off angles (long-offset and wide-azimuth acquisitions) could potentially be corrected with alternative separation algorithms in different domains that take take-off angles into account. For the simultaneous source separation in common offset gathers it is not possible to distinguish between arrivals from different take-off angles. The tests in the sensitivity study consider sequence deviations that are consistent for each source shot. In common offset gathers, each trace, however, results from different shot positions and, thus deviations from the estimated sequences are not consistent for multiple traces. This incoherency reduces the separation error even further. The presented tests confirm the stability of the sequence encoding for various noise-free scenarios with a stationary source. Yet, before field tests can be conducted, a full synthetic test to demonstrate the effect of noise, source motion, radiation patterns, and others should be conducted and is the subject of ongoing research.

A further aspect of sequence encoding that must be addressed is related to the spectral effects of spreading the air-gun signal over time. Although the sequence firing of an air-gun array can introduce small additional notches, these can be adequately recovered using appropriate algorithms as for instance the multifrequency algorithm by Ji et al. (2013). Furthermore, Haavik and Landrø (2015) argued that the variation of the source depth during acquisition enables acquiring seismic data with energy more evenly distributed within the main frequency band of the source output. Combining air guns at different depths to design firing sequences could enable these benefits for each single shot of sequence-encoded sources. To optimize the energy output of the firing sequences, additional restrictions for the air-gun firing times, for instance not to fire into the neighboring bubble, can also be considered for the sequence design. It is also important to note that, because the firing sequences include the free-surface ghosts and the bubble effect, the successful reconstruction of conventional seismic data from the sequence-encoded simultaneous source data is equivalent to a 1D designature process including debubbling and 1D deghosting. In addition, the optimization of the autocorrelations of the sequences also yield sequences that are more broadband and contain less notches (Figure 3.4e and 3.4g). Although the used multi-frequency separation method allows us to fill possible sequence notches (Mueller et al., 2015), having broadband encoding sequences could be an additional benefit for today's demanding broadband acquisition enabling the separation with a more broadband source signature.
Alternative optimization algorithms such as Monte Carlo methods can also be used for the optimization. In our optimization, we chose a simulated annealing approach as it allows us to deal with the huge parameter space (many possible firing times for each of the air guns) and converges to a local minimum. The use of additional optimization parameters (e.g., gun type, firing depth and others) expands this parameter space even further.

3.7 Conclusion

We demonstrated that optimized near-orthogonal air-gun firing sequences can be designed using a simulated annealing algorithm. The cost function that is minimized by the optimization method describes the orthogonality properties of two sequences, but can be extended to include additional sequences. The optimized near-orthogonal sequence examples show the capability of the method and the demonstrated uplift of the simultaneous source separation with the optimized sequence set shows the potential of air-gun sequence firing for marine simultaneous source acquisition. The method was also shown to be robust towards incidence angle variations and outperforms the simultaneous source separation for dithered, tuned air-gun sources up to incidence angles of 30°. Sequence encoding is still in the early stages of development, but it promises numerous benefits at very limited additional cost, such as source-side deghosting, denser source sampling and enhanced simultaneous source separation.

3.8 Acknowledgments

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References


Chapter 4

Turning the source ghost into a separate source

Abstract

Marine air-gun sources can be sequence-encoded by firing their individual elements independently over a short period of time. Using near-orthogonal firing sequences, whose crosscorrelation is minimal, as encoding sequences for multiple sets of air-gun sources enables to exploit their orthogonality as a separation feature. We show that by distributing air guns over depth from 5 to 30 m firing sequences can be designed whose direct, downgoing wavefield is close to orthogonal to its source ghost wavefield. We generate a set of such firing sequences by minimizing the crosscorrelation of these wavefields and optimizing their respective autocorrelations for having sharp peaks. The obtained, optimized firing sequences are then used for marine seismic source encoding. By adapting a multi-frequency algorithm originally developed for simultaneous source separation, we demonstrate that the ghost-source wavefield can be separated as a separate source from the direct, downgoing wavefield.
4 Turning the source ghost into a separate source

4.1 Introduction

A core objective of much of the recent advances in marine broadband seismic technology has been the attenuation or elimination of sea surface ghost reflections. This unavoidable reflection results in notches in the frequency spectrum both on the source as well as on the receiver side. Since sources and receivers typically are deployed at different depths, they are also associated with different sets of ghost notches. To recover the missing signal in the notches, different acquisition configurations and processing strategies have been developed. Almost all of these methods can be classified into two main categories: Multi-level methods, on the one hand, where multiple sources or receivers are distributed at different depths and gradient-based methods, on the other hand, relying on multicomponent sources and recordings.

On the receiver side, multi-level acquisition is achieved with either slanted streamers (Soubaras and Dowle, 2010) or with over/under streamer configurations deploying two streamers at different depths (Sonneland et al., 1986; Brink and Svendsen, 1987). The multicomponent methods on the receiver side rely on dual-sensor measurements recording not only the pressure but also particle acceleration. These measurements can be conducted either with dual-sensor ocean bottom cables (Barr and Sanders, 1989) or with dual-sensor towed streamers (Carlson et al., 2007; Caprioli et al., 2012; Day et al., 2013). Instead of using dual-sensor measurements, single-component pressure data can also be used to compute estimates of the vertical velocity and perform deghosting (Ferber et al., 2013; Momoh et al., 2016). Amundsen (1993) provides a thorough review of how the recorded wavefield can be separated into its up- and downgoing components using either multilevel or multicomponent data. The full potential of multicomponent measurements by measuring not only the vertical component but also the horizontal components of the particle velocity vector was demonstrated by Robertsson et al. (2008a), who also discuss the use of the full pressure gradient beyond deghosting for wavefield reconstruction.

On the source side, the majority of methods have made use of depth-distributed sources associated with different source ghost time delays. In the over/under technique, the source ghost is removed during subsequent processing combining the independently recorded data from two sources fired at different depths (Moldoveanu, 2000). Most broadband acquisition source configurations nowadays make use of dual-depth (Hopperstad et al., 2008) or multi-depth slanted air-gun sources (Shen et al., 2014; Telling et al., 2014) to directly align the downgoing wavefield and reduce the ghost effect by destructive interference and obtain a signature with only one peak. Within certain design criteria and for certain take-off angles, these multi-depth source methods create a notch-free source signal as an optimization result of
4.1 Introduction

the tradeoff of the ghost response and the aperture effect. Another method that makes use of time and depth distributed sources is described by Parkes and Hegna (2011b, 2011a), who sum the autocorrelations of the different ghost functions and perform a spectral normalization to obtain ghost-free seismic data.

The practical application of gradient-based methods on the source-side is more challenging, as it requires the use of dipole sources. Although actual marine dipole sources promise to bring similar benefits as seen on the receiver-side to the source side (Robertsson et al., 2008b), they are still in a developmental phase (Meier et al., 2015). However, dipole sources can be approximated by the combination of two closely-spaced monopole sources radiating the same wavefield but with opposite polarity (Robertsson et al., 2012). Halliday (2013) compares the different source-side deghosting methods and argues that if vertical source gradient data can be efficiently acquired, the source gradient deghosting scheme may be the most effective for broadband acquisition. Another approach for broadband marine seismic acquisition is the aim to obtain notch diversity in the amplitude spectra by variation of the source depth along the sail line as discussed by Haavik and Landrø (2015). Combining these deghosting techniques on the source and the receiver-side can finally lead to the acquisition of fully-deghosted, broadband data (Egan et al., 2007) and to ghost-free imaging (Sablon et al., 2013).

Whereas many of these recent advances in marine seismic broadband technology on the source side aim at the attenuation of the ghost reflection from the water surface, we suggest a method that makes use of the source ghost by turning it into a “separate source”, so that the wavefields can be separated in the vertical direction. We achieve this by distributing multiple air guns over depth (5 to 30 m) and encoding them with a firing sequence similar to the sequence encoding suggested by Mueller et al. (2015) for simultaneous source separation. We consider the resulting direct, downgoing wavefield and the purely upgoing wavefield, that is reflected at the sea-surface, as two different wavefields that are recorded by a receiver below the depth-distributed sources. Since the air guns are deployed at different depths and thus are associated with different source ghost time delays, the entire source ghost sequence or wavefield, which is the superposition of the ghosts of all fired air guns, is not a time-delayed, opposite polarity version of the direct, downgoing wavefield, as would be the case if all sources were deployed at the same depth. We use the sequence optimization method by Mueller et al. (2016a), to find a firing sequence whose source ghost wavefield is orthogonal to its direct, downgoing wavefield. Then we can use the simultaneous source separation method by Ji et al. (2012, 2013), which was adopted by Mueller et al. (2015) to exploit sequence orthogonality, to separate the source ghost wavefield from the direct, downgoing wavefield as a separated source.
However, since the source ghost wavefield cannot be dithered, as would be possible for two independent firing sequences, we need to use a different firing sequence from shot to shot to perform the separation using a coherency-based method. Our approach turns the source deghosting problem into a simultaneous source separation problem similar to the concept presented by Berkhout and Blacquièrè (2016), who also consider source-side deghosting as a deblending problem. Our method does not only enable deghosting, but it also yields two separate vertically distributed monopole sources, which could be used for the generation of vertical dipole source data for vector acoustic imaging techniques (Vasconcelos, 2013).

4.2 Methodology

4.2.1 Ghost-source concept

In conventional marine seismic acquisition, a number of air guns deployed at the same depth are fired together to generate the source signal. To attenuate any secondary signal from the bubble oscillations, air guns of different volumes associated with different bubble time periods are used to shape the source signal by constructive and destructive interference of the individual air-gun signatures. The resulting source configuration is known as a “tuned air-gun array” (Parkes and Hatton, 1986).

The source signal emitted from the air-gun sources is reflected at the sea surface. In general, the planar water/air interface acts as an almost perfect reflector at seismic frequencies with a reflection coefficient of $-1$ causing a polarity reversal of the reflected wavefield. Thus, any seismic signal generated by an air-gun source is followed by a time-delayed ghost reflection of opposite polarity, which can be considered as the signal from a virtual source positioned vertically above the air-gun source radiating a wavefield of opposite polarity (Figure 4.1). The time delay of this source ghost is given by:

$$t_{\text{delay}} = \frac{2z_s \cos(\phi)}{c_w},$$

with $z_s$ the firing depth, $\phi$ the take-off angle to the vertical and $c_w$ the sound velocity of water. The interference of this source ghost with the primary, direct, downgoing wavefield limits the bandwidth of the source signal and has led to the development of the afore-mentioned broadband technologies, that aim at the attenuation of this ghost reflection.

Instead of tuning an air-gun array by firing the individual air guns at almost the same time to generate a sharp source pulse, the individual air guns can also be fired
Figure 4.1: The marine seismic ghost reflection can be considered as the signal from a virtual source positioned above the sea surface radiating a wavefield of opposite polarity (Parkes and Hatton, 1986).

independently over a range of firing times resulting in a sequence of individual air-gun pops (Robertsson et al., 2008b; Abma and Ross, 2013; Mueller et al., 2015). When we now consider such sequence-encoded air-gun arrays, we can also distinguish between the direct, downgoing wavefield and the upgoing wavefield, which is reflected at the sea surface resulting in the source ghost wavefield. In a conventional marine seismic acquisition setup with all air guns deployed at the same depth, the source ghost wavefield is simply a time-delayed version of the direct, downgoing wavefield with opposite polarity, as the individual air guns are associated with the same source ghost time delays (illustrated on the left of Figure 4.2). However, if the individual air guns are distributed over depth, the resulting source ghost wavefield is not a time-delayed version of the direct, downgoing wavefield anymore. Figure 4.2 illustrates how the different source ghost time delays of the air guns fired at different depth, result in a different source ghost wavefield.

This crucial difference of the direct, downgoing source sequence and the reflected source ghost sequence, which is most prominent for vertical take-off angles, is key to separate both wavefields into a direct source and a secondary ghost-source. Mueller
4 Turning the source ghost into a separate source

Figure 4.2: Illustration of the ghost-source concept for sequence-encoded air-gun sources. Left: Conventional marine seismic acquisition setup with all air guns deployed at the same depth. Since the source ghost time delays of the individual air guns (dots) are the same, the reflected ghost-source sequence (blue) is simply a time-delayed version of the direct, downgoing wavefield (red) with opposite polarity. Right: When the individual air guns are distributed over depth, the resulting source ghost sequence (blue) is not a time-delayed version of the direct, downgoing wavefield (red), as the individual air guns have different source ghost time delays.

et al. (2015) demonstrated that sequence-encoding can be used as an additional feature to separate simultaneous sources. By using encoding sequences, which are near-orthogonal to each other, they achieve a significant improvement in the simultaneous source separation. If we can find firing sequences for depth-distributed sources, for which the direct, downgoing wavefield is close to orthogonal to the source ghost wavefield, we can separate the source ghost as a separate source. Thus, instead of
considering the source ghost as a bandlimiting, undesired feature that should be attenuated, we suggest to consider it as a “separate” source, the “ghost-source”, which - if successfully separated - enables up-down wavefield separation.

4.2.2 Optimization of firing sequence

To find a firing sequence, whose vertical-take-off, source ghost wavefield is close to orthogonal to its direct, downgoing wavefield, we adopt the approach introduced by Mueller et al. (2016a) to design near-orthogonal air-gun firing sequences for two independent simultaneous sources. Mueller et al. (2016a) use a simulated annealing algorithm to construct two firing sequences so their orthogonality properties are optimized. By varying the firing times of the individual air-guns, which are deployed at a fixed depth, they minimize the crosscorrelation of the two firing sequences and optimize their respective autocorrelations. The fundamental difference between the optimization of two independent firing sequences and the optimization of the source ghost sequence with respect to the direct, downgoing sequence, is that the source ghost sequence does not result from an independent firing sequence, but it follows inherently due to the respective ghost time delays of the individual air-gun sources. As a consequence, the orthogonality properties of the direct source sequence and the ghost-source sequence are in general relatively poor for random firing sequences. Whereas, two purely random firing sequences for two independent sources have good orthogonality properties on average (Mueller et al., 2016a). Thus, to be able to separate the ghost-source as a separate source, the thorough design of appropriate firing sequences is imperative.

There are two essential parameters that can be varied to design firing sequences having near-orthogonal ghost and direct source sequences for vertical take-off. If we assume that we can fire a certain number of air guns over a given range of time, these are their firing times and their firing depths (and possibly the air-gun volume). Each air gun yields a specific air-gun signature depending on its gun volume and its deployment depth, resulting in a characteristic bubble time period. By formulating an optimization problem, which evaluates the orthogonality properties of the ghost-source and the direct source for many different combinations of firing times and firing depths, we can find suitable firing configurations. Similar to the approach presented in chapter 3.2.1, we choose an optimization approach based on simulated annealing (Kirkpatrick et al., 1983) and minimize a cost function until it converges to a minimum. Assuming that for each firing sequence, we can fire a certain number
of air guns, \( g \), the optimization problem can be expressed as:

\[
\text{minimize } E_{\text{cost}}(t_g, W_g(z_s)) \\
\text{subject to } 0 \leq t_g \leq T_{\text{max}} \\
\text{and } W_g(z_s) \in W_{\text{sig}}(z_s),
\]

(4.2)

where \( E_{\text{cost}} \) is the chosen cost function that is minimized, \( t_g \) is the firing time of the individual air guns limited by a given maximum firing delay \( T_{\text{max}} \), \( W_g(z_s) \) is the signature of the respective air gun which is chosen from the family of possible air-gun signatures \( W_{\text{sig}}(z_s) \) and \( z_s \) is the deployment depth of each of these air guns (limited by the possible air-gun firing depth in the range of \( z_{s_{\text{min}}} \) to \( z_{s_{\text{max}}} \)).

The cost function, that is minimized, evaluates the crosscorrelation of the direct source sequence, \( S_D \), and the source ghost sequence, \( S_G \) and their respective autocorrelation properties. Following chapter 3.2.1, we define it as:

\[
E = \gamma \cdot CC + (1 - \gamma) \cdot (AC_D + AC_G), \quad 0 \leq \gamma \leq 1,
\]

(4.3)

where \( CC \) is the term that evaluates the crosscorrelation of the direct and ghost sequence by minimizing its absolute peak and its normalized L2-norm. The terms \( AC_D \) and \( AC_G \) quantify the autocorrelation properties of the sequences. These autocorrelations terms serve to minimize the L2-norm in a window around the central peak to make it sharper. These terms also minimize the peak-to-sidelobe ratios of the autocorrelations. The exact definition of the \( CC \) and \( AC \) terms is equivalent to the definition in chapter 3.2.1. The weighting factor \( \gamma \) determines which term is most relevant for the optimization.

Although the basic steps of this optimization closely resemble the optimization for two independent firing sequences as discussed in chapter 3, there are some important differences. Since we consider the direct and the ghost-source wavefield as two separate source sequences, the direct source sequence is dominated by positive amplitudes, whereas the ghost-source sequence is dominated by energy of the opposite amplitude due to the negative reflection coefficient of the sea surface. Their resulting autocorrelations for random firing configurations (i.e., random firing times and deployment depths) show significantly more sidelobe energy and broader autocorrelation peaks than what is the case for firing sequences containing both direct and ghost-source energy. Thus, to make the ghost-source sequence orthogonal and to be able to separate its signal from the direct, downgoing wavefield with a sparse inversion algorithm, it is not only required to minimize their crosscorrelation peaks, but also crucial to shape their autocorrelation peaks and attenuate any side-lobe energy that could otherwise be interpreted as signal.
4.3 Ghost-source sequence optimization

In order to generate air-gun firing sequences for depth-distributed air-gun sources, we use six different air guns of varying size, that are typical for conventional air-gun arrays. Their notional signatures were modelled at different depths. Since we need to distinguish between the direct, downgoing pulses and the signal reflected at the sea surface, we generate two different catalogues of air-gun signatures. One catalogue contains the modelled air-gun signatures for the direct, downgoing pulses without the source ghost and the second catalogue contains the source ghost signatures for the same air guns, generated by convolution with the source ghost functions for the respective firing depths. The modelled, notional signatures in both catalogues were then extrapolated to a receiver depth of 1000 m to obtain far-field signatures for vertical take-off and filtered with a 120 Hz high-cut filter.

The catalogues, that we use here, contain the notional signatures for 6 different air guns modelled for 26 different firing depth levels ranging from 5 to 30 m in steps of 1 m, so that each catalogue contains 156 different signatures. Figure 4.3 shows the resulting direct, downgoing and ghost signatures for one specific air gun with a 280 cubic inch firing volume. Besides the primary pulses, the air-gun signatures include the signal of the oscillating bubble, which swells and shrinks multiple times before it either dissolves or breaks at the sea surface. The bubble time period is a function of the air-gun volume, the firing pressure and the deployment depth of the air gun (Parkes and Hatton, 1986). The dependence of the oscillation period of the bubble on the firing depth is also visible in Figure 4.3.

For the generation of firing sequences from these air-gun signatures, we assume that we have three sets of these six different air guns available that we can each fire once over a given range of time at a specific depth. For the sequence examples presented here, we use a time sampling of $dt = 4 \text{ ms}$ for the signatures. First, we compute a random firing sequence by firing each of the 18 air guns exactly once during a period of 1 second at a random depth. Both the random firing time and the random firing depth are drawn from a uniform distribution. Figure 4.4a and 4.4b show the resulting direct, downgoing source wavefield and the corresponding source ghost wavefield for vertical take-off. Their normalized autocorrelations (Figure 4.4c and 4.4d) contain significant sidelobe energy with strong sidelobe peaks (0.253 and 0.227). Their zero-lag autocorrelation peaks are also relatively wide, which is undesirable for the intended separation algorithm using a sparse inversion approach. Their normalized crosscorrelation shows a number of peaks with an absolute maximum of 0.485. It is clear, that for this random firing configuration, we cannot consider the direct, downgoing source wavefield to be close to orthogonal to the
4 Turning the source ghost into a separate source

Figure 4.3: Direct, downgoing signatures (left) and ghost signatures (right) for an air gun (280 cubic inch) fired at different depths (5 to 30 m). These notional, far-field signatures for vertical take-off, which are filtered with a 120 Hz high-cut filter, illustrate the dependence of the bubble time period on the firing depths.

We have generated a number of random firing sequences and evaluated the correlation properties of their direct, downgoing wavefields and their respective ghost-source wavefields. The correlation properties of the random firing sequence example presented in Figure 4.4 can be considered as representative. This clearly demonstrates that an optimization of the firing sequences is necessary to generate firing sequences whose direct and ghost-source wavefields are near-orthogonal.

We start the optimization procedure by computing the cost function describing the orthogonality properties of the direct and ghost-source sequence for this initial
4.3 Ghost-source sequence optimization

![Diagram showing a) Direct, downgoing source wavefield, b) Ghost source wavefield, c) Autocorrelation direct source (sidelobe max.: 0.253), d) Autocorrelation ghost source (sidelobe max.: 0.227), e) Spectrum direct source, f) Crosscorrelation direct & ghost source (absolute max.: 0.465), g) Spectrum ghost source]

**Figure 4.4:** Random air-gun firing sequence of 18 air guns distributed over depth (5–30 m), each fired exactly once during a period of 1 second with firing times drawn from a uniform distribution: (a) Resulting direct, downgoing wavefield. (b) Resulting upgoing, source ghost wavefield. (c,d) Autocorrelations of a and b. (e,g) Spectra of the two sequences. (f) Crosscorrelation of a and b.

A random firing sequence (Figure 4.4) according to equation 4.3. Then, a random air gun is chosen and a new random firing time is attributed to it in the given firing range of 1 second. In a next step, the orthogonality properties of the direct and ghost-source sequence for this new firing sequence is evaluated. If the cost function is reduced or if the increase of the cost function falls within the acceptance range of the simulated annealing algorithm, the new firing configuration for the air gun is accepted. The flowchart in Figure 4.5 illustrates the basic steps of the optimization procedure. After every 20 iterations, the optimization algorithm can also vary the firing depth for one air-gun source to guarantee that the deployment depth is also
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used as an optimization parameter. When the cost function converges to a local minimum, which is the case if the cost function is not reduced for a certain number of iterations, the optimization procedure is stopped and the corresponding firing configuration is retained. Figure 4.6a and 4.6b show the direct and ghost-source sequences for a firing configuration which was obtained after several thousand iterations. Both autocorrelations show significantly lower sidelobe energy with its sidelobe peaks reduced to 0.126 for the direct source sequence and to 0.130 for the ghost-source sequence (Figure 4.6c and 4.6d). Additionally, both autocorrelations have much sharper autocorrelation peaks than seen before for the random firing configuration in Figures 4.4c and 4.4d. The most important improvement can however be observed for the crosscorrelation, which was substantially minimized with the absolute peak reduced from 0.485 for the random firing configuration to 0.111 after the optimization. After the optimization, the direct, downgoing wavefield can be considered close to orthogonal to the ghost-source sequence, which can now be exploited for their separation. Figure 4.7 shows the firing depths of the 18 air guns after the optimization. The firing configuration includes many different deployment depths, with a slight tendency to deeper deployment depths, which have a larger ghost delay time that can be exploited for the ghost sequence orthogonality.

4.4 Separation of the ghost-source from the direct, downgoing wavefield

Now that we have demonstrated that by using the optimization approach presented in chapter 3 we can find an optimized firing sequence for depth-distributed air-guns, whose direct, downgoing wavefield is close to orthogonal to its ghost-source wavefield, we demonstrate how we can separate the ghost-source from the direct source adapting the simultaneous source separation method by Mueller et al. (2015). Although we use a separation method for simultaneous source data, it must be clarified that there is an intrinsic difference between sequence-encoded, simultaneous source data and the ghost-source concept. Whereas conventional, simultaneous source acquisition implies the acquisition of data from two independent sources, where one source can be dithered, the ghost-source sequence results from the same air-gun firing sequence as the direct, downgoing source. Thus, the ghost-source sequence can not be independently dithered and we must therefore use a different optimized firing sequence from shot to shot. However, using the described optimization method, we have a tool at hand to generate a number of optimized firing sequences having near-orthogonal direct and ghost-source wavefields.
4.4 Separation of the ghost-source from the direct, downgoing wavefield

Figure 4.5: Flowchart illustrating the basic steps of the optimization procedure with the simulated annealing (S.A.) algorithm.

For the synthetic data example performed in this study we have selected 50 optimized firing sequences (with different depth-distribution) based on their orthogonality properties from a large number of optimized firing sequences. Figure 4.8 shows the correlation properties of the selected firing sequences sorted by ascending crosscorrelation peak value. The selection of these 50 firing sequences was primarily based on their crosscorrelation maxima and secondarily on the peak-to-sidelobe ra-
Figure 4.6: Optimized air-gun firing sequences of 18 air guns distributed over depth (5 – 30 m), each fired exactly once during a period of 1 second: (a) Resulting direct, downgoing wavefield. (b) Resulting upgoing, source ghost wavefield. (c,d) Autocorrelations of a and b. (e,g) Spectra of the two sequences. (f) Crosscorrelation of a and b.

Here, we test the ghost-source separation by generating synthetic shot records of a North sea model (Figure 4.9a) for sources at a depth of 6 m and receivers placed at a depth of 20 m (Mueller et al., 2015). It is important to note that we assume a stationary monopole source, which does not account for the aperture of the depth-distributed air-guns sources and their possible motion during the sequence firing.
4.4 Separation of the ghost-source from the direct, downgoing wavefield

Figure 4.7: Firing depths of the 18 air guns after optimization for ghost-source orthogonality.

Figure 4.8: Correlation properties of 50 selected, firing sequences optimized for having near-orthogonal direct and ghost-source wavefields. The firing sequences are sorted by their crosscorrelation peaks (black) and were chosen based on the quality of their correlation properties. The blue and the red curves show the respective autocorrelation sidelobe maxima for the direct, downgoing wavefield and the ghost-source sequence.
The synthetic data were modelled with a finite-difference code without a free-surface and a time-sampling of $\Delta T = 4$ ms. We sort the data into common offset gathers with a source spacing of 40 m and window them on a focus area containing the major structures with three tilted fault blocks - the central one containing a flat oil/water contact (as indicated in Figure 4.9a by the dashed box). The source encoding is achieved by using the 50 optimized firing sequences including both the direct and the ghost wavefields as encoding source signatures for the respective source position. We do not include a free-surface in the modelling, but instead include the ghost reflection in the encoding sequences. This also enables using only the direct or ghost wavefields as encoding source signatures to generate reference data for the simultaneous source separation. Additionally, we model the data with sources at only one specific depth since the time delays due to the different air-gun firing depths are included in the encoding sequences. The final sequence-encoded data composed of 50 traces are shown in Figure 4.9b. The separation method considers the direct, downgoing sequence and the ghost-source sequence as two separate sources and separates them based on a sparse Radon inversion. For the presented separation examples, 200 iterations of the sparse inversion method were performed. Since the separation method solves for an impulsive Radon model, the separated data are convolved with a standard air-gun signature. Figure 4.9b and 4.9e show the separated, 500 m common offset data of the direct and the ghost-source. The respective difference plots between the separated data and the data as if acquired by a true direct and ghost-source are shown in Figure 4.9c and 4.9f. The separation error of 14% shows that the ghost-source and the direct source can be separated as two different sources in the vertical take-off approximation. These errors will further be reduced after subsequent stacking and migration.

This example demonstrates that by using depth-distributed air guns, which are fired with an optimized firing configuration in terms of firing depth and firing time, we can encode the ghost-source such that it can be separated as a separate source. This ghost-source separation method thereby performs 1D-deghosting. Within the limits of the vertical take-off assumption, it also yields a separate source as if acquired with a virtual source above the sea surface (as illustrated in Figure 4.1).

### 4.5 Discussion

We have found that by sequence firing of depth-distributed air guns we can encode the ghost-source wavefield such that it can be separated from the direct, downgoing wavefield. Since the direct and ghost-source wavefield are resulting from the same
Figure 4.9: Separation of source ghost from direct, downgoing wavefield with the multifrequency method by Ji et al. (2013) and used by Mueller et al. (2015): (a) P-wave velocity model of North Sea geology with the dashed box marking the focus area considered for this ghost-source separation. (b) Separated direct, downgoing wavefield. (c) The difference between the original data and the reconstructed data. (d) Sequence-encoded 500 m common offset data with a set of different optimized firing sequences (as shown in Figure 4.8). (e) Separated (upgoing) ghost-source data. (f) The difference between the original data and the reconstructed data (e).
4 Turning the source ghost into a separate source

air guns, it is intuitive that a random firing configuration does not provide the required orthogonality properties. However, Mueller et al. (2016a) introduced a method to generate optimized near-orthogonal firing sequences for two independent simultaneous sources and demonstrated that this enables an additional uplift for the separation of sequence-encoded simultaneous sources. For the ghost-source concept presented here, such an optimization approach is imperative to find a suitable firing configuration. Furthermore, we make use of the firing depths of the individual air guns as an additional optimization parameter and exploit their associated ghost time delay differences to make the ghost wavefield orthogonal to the direct wavefield.

As noted by Mueller et al. (2015), the key to separate the direct and the ghost-source based on sequence orthogonality lies within the multifrequency algorithm by Ji et al. (2013). Since dithering cannot be used as a separation feature for the ghost-source, a single-frequency algorithm, which handles each frequency component separately, would not be sufficient for the separation. The multifrequency method also allows us to deal with spatially aliased data with a 40 m shot spacing and to fill any notches present in the sequence spectra.

A possible limitation of the method presented here is its angular dependency on the take-off angle. The optimization of the firing configuration is performed for vertical take-off angle and also the presented synthetic data examples assume vertical take-off. For angles very close to the vertical, the resulting ghost time delays might be small enough to separate the ghost-source based on this vertical take-off approximation. However for larger take-off angles the source ghost time delay variations result in different direct and ghost sequence wavefields that might not have the same quality of orthogonality properties, particularly for deeper sources. Crucial for the successful separation of sequence-encoded data is the correct estimation of the transmitted firing sequence. Near-field measurements of the individual air-gun signatures can help to significantly improve the estimated far-field sequences (Ziolkowski et al., 1982) and to enable a successful separation of the ghost-source.

In the presented examples, the time delays of the guns with respect to a certain reference depth are included in the decoding sequences. Here, we are also assuming that the guns are aligned vertically and fired from a stationary source with vertical take-off only. Further tests will also be required to demonstrate the effect of noise, the radiation pattern and possibly the source motion.

An additional benefit of the optimized, depth-distributed air guns follows from the optimization of the autocorrelations for having sharp autocorrelation peaks and limited sidelobe energy. The resulting optimized firing sequences have a more broadband signal with flatter spectra containing more low and high frequencies. Landrø and Amundsen (2014) discuss the effect of the tow-depth on the bandwidth of ma-
rine seismic acquisition with the dualism of the free-surface effect favoring deep towed sources and the bubble time period favoring shallower tow depths. Haavik and Landrø (2015) use an inversion approach to find the optimal source depths over a sequential series of shots for broadband marine seismic acquisition by varying the source depth for different shot positions. Our method combines multiple air-gun sources at different depths for each shot position and thereby provides similar benefits for broadband acquisition.

Finally, a practical limitation arises from the weather, which can have a severe impact on the flatness or roughness of the water surface lowering the reflection coefficient of the sea surface. However, as long as the strength of the ghost reflection, i.e. the reflection coefficient, is known it could be included in the separation process by using the actually emitted ghost wavefield recordings. A possible limitation of the sequence-encoding method in general is the reduction of the peak amplitude resulting from array detuning (Hopperstad et al., 2014). Nevertheless this might only be an issue at the low frequencies (less than 5–10 Hz), where the optimized firing sequences contain more energy as a result of the optimization of the autocorrelations. For the mid to high-frequency range this should not be a problem, as there should be excess energy in this part of the spectrum (Laws et al., 2008).

A vital advantage of our ghost-source separation method is that we obtain two separate source wavefields after the separation similar to Berkhout and Blacquièrè (2016). These vertically-aligned source wavefields result from the same horizontal source position and could at least for low frequencies theoretically be used for the generation of vertical gradient data (Robertsson et al., 2008a). Extending our optimization and separation method to include additional simultaneous sources, which are also encoded with near-orthogonal firing sequences, this could enable similar wavefield gradient techniques on the source-side as known on the receiver-side such as source-side wavefield reconstruction (Halliday et al., 2012), the application of vector acoustic imaging techniques (Vasconcelos, 2013) and eventually the acquisition of full wavefield, vector-acoustic seismic data.

4.6 Conclusion

We have demonstrated that using sequence-encoded, depth-distributed air-gun sources, we can optimize the direct, downgoing wavefield to be close to orthogonal to the ghost-source wavefield. Using the firing time and the deployment depths of the air guns as optimization parameters, we minimize a cost-function describing the orthogonality properties of the direct and ghost-source sequences. By using a different
4 Turning the source ghost into a separate source

optimized firing sequence from shot to shot, we show how the ghost-source can be separated from the direct source as a secondary wavefield using a multi-frequency algorithm. Although the firing configuration is optimized for the vertical take-off angle approximation and the separation based on sequence orthogonality may not work for larger take-off angles away from the vertical, it demonstrates a new application of sequence encoding for marine seismic acquisition. By turning the source ghost into a separate source instead of aiming at its attenuation, our source ghost separation method may enable numerous benefits ranging from up-down wavefield separation to source-side gradient techniques such as wavefield reconstruction and novel vector-acoustic imaging techniques at potentially very limited additional costs.

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References


Turning the source ghost into a separate source


Chapter 5

Conclusions & Outlook

5.1 Thesis conclusions

In this dissertation, we developed encoding techniques for marine seismic sources and
demonstrated the concepts for simultaneous source acquisition and separation using
synthetic data. This work shows how sequence orthogonality can be exploited as an
encoding feature for simultaneous source acquisition, yielding a significant improve-
ment in simultaneous source separation. To guarantee the orthogonality properties,
we developed an optimization method enabling the generation of near-orthogonal
marine seismic source encoding sequences. The application of the sequence opti-
mization technique also led to the development of the ghost-source method demon-
strating one of the many applications of source encoding.

In chapter 2, we used the concept of firing the individual air guns of an air-gun
array independently over a short period of time and demonstrated how marine source
encoding can be used in combination with time-dithering for simultaneous source
separation. The separation method is based on sparse Radon inversion, mapping
the data into a domain where the coherent energy is sparse. We demonstrated
that the sequence orthogonality cannot easily be exploited by a single-frequency
algorithm, but that a time constraint is required to take advantage of the correlation
properties of firing sequences. By using a multifrequency method, we show how
the simultaneous source separation can be significantly improved, as demonstrated
through the synthetic examples for which the separation error is reduced by more
than a factor of two compared to the use of ditherd, tuned air-gun sources. The
multifrequency algorithm is not only key to include the required time constraint,
but also facilitates dealing with realistic shot spacings, that otherwise would result
in spatially aliased separation. Although the spreading of the source signal over
time introduces notches in the spectra of the encoding sequences, the joint inversion
of multiple frequency components in the algorithm enables filling these zeros in
the spectra and recovering the full bandwidth of the signal, in addition to taking
advantage of the orthogonality properties.

The encoding sequences employed in the work presented in chapter 2 were con-
structed by convolution of a bandlimited Ricker wavelet with a set of Kasami sequences known for having minimal crosscorrelation and optimal autocorrelation properties. Since such sequences cannot be emitted by marine seismic sources, we addressed the question of how real air-gun firing sequences can be designed for having such desired orthogonality properties in chapter 3. In the design process, we vary the firing times of the individual air guns and generate many different pairs of encoding sequences. The orthogonality properties of the different sequence pairs are measured by means of a cost function that evaluates the respective cross- and autocorrelations. By minimizing the cost function using a simulated annealing algorithm we find optimized near-orthogonal air-gun firing sequences with the desired minimized crosscorrelations and autocorrelations with a maximized peak-to-sidelobe ratio and a sharp peak. Although purely random firing sequences show good orthogonality properties on average, we show that using the optimized near-orthogonal air-gun firing sequences yield a consistent and controllable separation improvement compared to random air-gun encoding sequences. Furthermore, the optimization for sharp autocorrelation peaks yields firing sequences with flat spectra containing more energy at the desired low-frequency end of the spectrum.

It is important to note, that although in the presented examples we use the same set of air-gun firing sequences for all shots and apply a time-dithering to one of the sources, the explicit dithering of one source is not required if the firing sequences are changed from shot to shot. The time-dithering was maintained for better comparability of the sequence-encoded sources to the conventional acquisition with tuned air-gun arrays. The optimization method enables the generation of many near-orthogonal air-gun sequences, so that they can be varied from shot to shot. In addition, using a different firing sequence for each shot position reduces the effect of noise, because any noise generated as part of the correlation process is random and results in energy that is incoherent in the Radon space.

In chapter 3, we also demonstrated the robustness of the sequence encoding methods in terms of a number of practical aspects that could pose limitations to the method. Changes in the transmitted sequences, which can be caused by amplitude variations or the failure of a gun, result in separation errors, since a different firing sequence was assumed in the separation process than the one that was actually emitted. Although using the intended firing sequences instead of the actually transmitted firing sequences in the separation algorithm causes higher separation errors as expected, the synthetic examples still demonstrate an improvement of employing sequence-encoding for simultaneous source separation compared to conventional tuned air-gun arrays. The same observation holds for separation errors arising from take-off angle variations of the sequences due to the different source ghost delays.
5.1 Thesis conclusions

Since in the separation process the firing sequences for vertical take-off are used, the separation error increases with take-off angle. Still, the separation results with sequence-encoded sources for take-off angles up to $30^\circ$ are found to outperform the separation results with a tuned air-gun array for vertical incidence. These findings are a substantial corroboration of the potential of sequence-encoding techniques. Furthermore, it is noteworthy that the discussed separation errors are obtained pre-stack. A further reduction of any remaining separation artefacts is likely achieved after imaging.

In chapter 4, we introduced a new ghost-source concept that combines the developments of the previous chapters. By encoding air guns distributed over depth in the water column (5–30 m) and adapting the sequence optimization method developed in chapter 3, the ghost wavefield can be designed to be near-orthogonal to the direct, downgoing wavefield by exploiting the different ghost time delays of air-gun elements deployed at different depths. Subsequently, we can then apply the separation method developed for simultaneous source separation in chapter 2 to separate the ghost-source from the downgoing wavefield. This application of sequence encoding critically relies on the proposed sequence optimization method in two ways: First, random firing sequences do not offer the required orthogonality properties of their ghost and direct, downgoing wavefields. Second, since the ghost wavefield cannot be dithered, as can be done for two independent simultaneous sources, the variation of the firing sequence from shot to shot is compulsory for a coherency-based separation method. Only the optimization method enables the necessary generation of a whole set of firing sequences with the required correlation properties for the ghost-source separation. Although the firing sequences for the presented ghost-source concept are optimized for vertical take-off, it demonstrates a new application of sequence encoding for source deghosting. In addition, the successful separation of the ghost-source as a separate source, enables a way of acquiring two vertically aligned sources simultaneously, which could be used for the generation of vertical source gradient data.

In summary, by bringing encoding techniques to the marine seismic source, the research presented in this thesis breaks with the established practice of requiring a single, sharp source peak. Our proposed source signatures offer a fresh perspective to solve some long-standing challenges of marine seismic acquisition on the source side such as source-side deghosting and source-side reconstruction and constitutes crucial enabling technology for full-wavefield vector-acoustic acquisition.
5 Conclusions & Outlook

5.2 Future outlook: Practical implementation

The research presented in this dissertation provides a practical framework for testing the encoding of marine seismic sources. Nevertheless there are a number of practical, technical aspects that must be addressed to realize the acquisition with sequence-encoded air-gun arrays. The following section provides a discussion of these aspects and includes recommendations for their solution and implementation.

5.2.1 Simultaneous source acquisition with encoded sources

As discussed in chapter 1, the listening time restricts the shot time interval in marine seismic acquisition. Since in conventional marine seismic acquisition with one tuned air-gun array using a single sharp source pulse the listening time is 10 s, a sequence-encoded source with a 1 s firing sequence would require a total recording time of 11 s, so that the equivalent 10 s of data can be recovered from the sequence-encoded data. Thus, the length of the firing sequence also has a (limited) effect on the required listening time. In the examples presented in this work, the maximum allowed firing delay of the individual air guns was 1 s, resulting in a slightly longer sequence length than 1 s due to the length of the individual air-gun signatures. Although using longer firing sequences would generally result in better orthogonality properties, there is a practical limitation to the desired sequence length, particularly for moving air-gun sources, which spread the signals over time and space. We found that firing sequences of 1 s provided the best results in terms of sequence orthogonality and practical feasibility (given certain limitations of the length of time windows that could be processed).

With regard to simultaneous source acquisition with dithered air-gun sources, the time dithers of the secondary source are typically on the order of ±0.5 s. If one again considers the necessity of a 10 s listening time for each source, the shot time interval is prolonged by the respective dither. Using sequence-encoded sources with alternating firing sequences makes the dithering redundant. If firing sequences of 1 s length are used, the required listening time is 11 s and thus only 0.5 s longer compared to dithered, tuned air-gun arrays. For future acquisition scenarios with more than 2 sources, the separation of time-dithered simultaneous sources with a coherency-based approach becomes more difficult. Since sequence-encoding potentially provides better separation results compared to time-dithered, tuned air-gun sources, sequence-encoding could therefore be the technique required to enable the acquisition of many simultaneous sources with the necessary separation quality.

Another important aspect to be considered for sequence-encoded air-gun sources,
is the reduction of their emitted acoustic energy due to the detuning of the array (Laws et al., 1988). Hopperstad et al. (2014) discuss this aspect by comparing the mean acoustic energy output of conventional peak-tuned air-gun arrays compared to detuned arrays. However, further research is required on how to mitigate this reduction of the emitted energy during data processing and under which circumstances the reduction poses a signal-to-noise problem. On the other hand, the reduction of the peak amplitude can also be considered as a positive effect, in particular with regard to potential negative environmental impacts (Abma and Ross, 2013) or in terms of requiring a shorter listening time with respect to the previously discussed consideration of the shot time interval (Abma and Ross, 2015). Nevertheless, the full effect of the reduction of the emitted acoustic energy and the peak pressure level in terms of penetration depth needs to be investigated and verified by field tests. If additional energy output will be required, more air-gun sources or clusters of tuned air-gun sources could be considered as individual firing elements in the sequence design to image deeper targets.

Since the separation results of the sequence-encoded, simultaneous sources obtained with the presented separation algorithm are sensitive to the accuracy of the firing sequence estimates, the employment of near-field hydrophones could be critical to record firing time deviations and gun failures and to correct for such effects. Even if the emitted sequences differ from the intended firing sequences, an accurate recording of the actually emitted sequences could still ensure the required separation results. In the presence of noise, an adaptation of the separation parameters, particularly of the sparsity threshold, could potentially improve the separation results.

5.2.2 The implementation of time-windowing

One limitation of the multifrequency separation method is its computational cost. The solution to the large system of equations includes the implicit inversion of the operator matrix containing the basis functions as part of the separation process. Since the matrix is not sparse, the inversion process has significant memory requirements. The size of the matrix scales, among other parameters, with the number of time samples, the number of sources and the number of neighbouring frequency components used in the multifrequency separation algorithm. The separation thus becomes more challenging when longer time windows are processed. Since the length of the firing sequences also directly affects the length of the time windows that need to be processed, longer firing sequences pose an additional computational challenge for the separation method with the multifrequency algorithm. In the long term, the development of time-domain implementations of the separation method should be
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a research objective, although they are expected to be associated with even higher computational costs and memory requirements. To solve the implementation problem of the time-windowing with the multifrequency method, we suggest the following two approaches:

First, it should be tested to which extent enhanced computational techniques for the solution of such large systems of equations can be exploited. Adapting the existing separation code for the use of smart parallelized solver libraries could enable the inversion of the operator matrices on supercomputers providing the necessary memory resources. For real sequence-encoded seismic data, a large number of these larger systems of equations needs to be solved, but with the further evolution of computational resources, it should only be a matter of time until optimized inversion techniques are capable of performing this task in an acceptable amount of time.

Second, instead of inverting complete data windows of full traces, time windows of the sequence-encoded data could be processed separately. Since the seismic data recordings do not result from a spike-like source but from an extended source sequence, overlapping time-windows of data must be processed. This overlap of the individual time windows poses the key challenge of the time-windowing solution. If one considers the acquisition with firing sequences of 1 s and data windows with a length of 2 s, then individual data windows with a length of 3 s would have to be processed and one would have to deal with an overlap that is at least as large as the sequence length of 1 s. The implementation of this time-windowing approach would require the processing of each individual time window, followed by the combination of the overlapping part at each iteration and the removal of the separated energy from the residual. Although the combination of the overlap could possibly be handled by tapers, the implementation of this, so that the overlapping part is correctly removed from the neighbouring time window, is not straightforward. Particularly, if earlier windows contain more and stronger reflections, while later windows contain less or weaker reflections, separations artefacts could occur, if different events are picked in the overlapping windows due to the limitation of strongest components that the sparse inversion is solved for. All these considerations show that the implementation of a time-windowing solution is challenging and that this remains a technical aspect to be solved for the practical application of marine seismic source encoding techniques.

5.2.3 The effect of the radiation pattern and source motion

An important characteristic of an air-gun array is its radiation pattern. Although, in the current thesis, we assume a point source for the demonstration of the pos-
5.2 Future outlook: Practical implementation

Possible applications of encoding techniques and their benefits, the radiation pattern should be more thoroughly investigated in future theoretical and practical research of sequence-encoded air-gun sources. If the effect of the radiation pattern needs to be corrected for, the radiation pattern or take-off angle corrected sequences could possibly be included in the separation algorithm. Figure 5.1 shows the far-field power spectra for different take-off angles and azimuth within a $20^\circ$ cone for a stationary tuned and a sequence-encoded air-gun array at 6 m depth. It is clear that the directivity of a sequence-encoded air-gun array should be investigated in future research.

With typical vessel speeds of 2–3 m/s during seismic acquisition, the encoding with sequence length of approximately 1 s should have a limited effect on the spatial spreading of the source energy over time compared to the overall extent of the array. However, since typical arrays for conventional acquisition extend up to 15 m in inline and crossline direction (Dragoset, 2000; Calderón Agudo et al., 2016), the spatial extent of the array should have a larger impact on the radiation pattern than the sequence firing. For source encoding, the air guns in an array could potentially be repositioned, spaced closer together or arranged so that their motion during sequence firing is compensated for by their position within the array.

To account for the true radiation pattern of the sequence-encoded air-gun array in synthetic examples, the exact positions of the individual air guns need to be modelled. Haavik et al. (2016) recently demonstrated how this can be implemented using finite-difference methods and wavefield injection (Robertsson and Chapman, 2000). Following their two-step approach, the air-gun array radiation pattern (including the sea surface reflection) can be analytically extrapolated to a recording surface just underneath the source array. In a second step this surface is then used as injection surface to inject the recorded wavefield and to generate the synthetic data for the desired subsurface model.

In the sensitivity study presented in chapter 3, we evaluated the effect of the take-off angle on the separation errors due to the changes in source ghost delay. In addition to the effect of the source ghost, the radiation pattern for different take-off angles is also affected by the spatial distributions of the individual air guns (Hopperstad et al., 2008). Since our separation method uses the modelled vertical take-off sequences for the separation, the separation error for sequence-encoded data increases with increasing take-off angles. Although the presented analysis showed that the separation errors at take-off angles of $30^\circ$ are still below the separation errors with tuned air-gun sources for vertical incidence, new solution strategies to deal with the effect of the radiation pattern can be developed. One approach could be the use of firing sequences that are modelled for take-off angles away from the
Figure 5.1: Illustration of the directivity of an air-gun array. Top: Far-field power spectra within a 20° take-off cone of an air-gun array consisting of 3 subarrays with 8 m separation at a depth of 6 m. Each subarray is composed of 6 different air guns with a 3 m separation. Their signatures are shown in Figure 3.1. The spectra of a tuned air-gun array are shown in blue, whereas the spectra of a sequence-encoded air-gun array are shown in red. The spectra of a tuned air-gun array are tuned at 30 Hz. The difference between the maximum and minimum of the shown power spectra at each frequency is obvious that the sequence-encoding has an effect on the radiation pattern. The spectra of a sequence-encoded air-gun array are shown in red. The spectra of a tuned air-gun array are shown in blue. The difference between the maximum and minimum of the shown power spectra at each frequency is obvious that the sequence-encoding has an effect on the radiation pattern.
vertical. Although this comes along with a small increase of the separation error for near vertical take-off angles, it mitigates the separation artefacts for larger take-off angles. Yet another solution could be the implementation of the separation method in a different data domain. Using different gathers, the radiation pattern could be accounted for by using corrected firing sequences as a function of the take-off angle associated with the observed slowness of a reflection event.

5.2.4 Practical aspects of the ghost-source concept

The depth distribution of the air-gun sources required for the source ghost concept poses a more challenging task for the technical realization, especially since this concept cannot be realized with the fixed-depth subarrays used in conventional acquisition. The set of optimized firing sequences, used in chapter 4 to change the firing sequence from shot to shot, also assumes that the depth distribution of the air guns can be changed from shot to shot. Although allowing for the change of the depth distribution for subsequent shots provides an additional degree of freedom that can be exploited to achieve sequence orthogonality, it is not required for the ghost-source concept. Theoretically, it is also possible to predefine a depth distribution of the air-gun sources and adhere to these firing depths for the optimization of a set of ghost-source firing sequences.

Nevertheless, the source ghost encoding requires a certain minimum number of different firing depths to make use of the different source ghost delay times. The effect of the radiation pattern for depth-distributed sources should be more severe than for the encoding of conventional air-gun subarrays deployed at a fixed depth. Even though the orthogonality properties of the direct and ghost-source wavefield deteriorate with increasing take-off angle, future separation algorithms that account for the radiation pattern could stabilize the ghost-source separation for the relevant part of the source signal cone.

5.3 Future outlook: Research perspectives

After addressing a number of practical and technical aspects in the previous section, we discuss the potential of more advanced marine seismic source encoding techniques and applications that may become feasible in the future.
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5.3.1 Development of marine seismic vibrator technology

The encoding techniques developed in this dissertation are tailored for the use of air-gun sources, since they currently represent the only marine seismic source technology that is commercially available and guarantees the required energy output for the desired seismic spectrum. The environmental impact of air-gun sources on marine life has been questioned in recent years (Richardson, 1995) such that the use of air-guns has even been banned in certain areas. However, spreading the energy output over time, as is achieved by encoding an air-gun array, significantly decreases the peak pressure level also from air-gun sources (Abma and Ross, 2013, 2015). Since the peak amplitude output of marine vibrators is consistently lower than for conventional air-gun arrays, this has also revived the development of the marine vibrator technology (Pramik, 2013; Pramik et al., 2015; Wei, 2015). Although current vibrator technology already provides sufficient energy output in the mid-frequency range, it still lacks the required low-frequency output to be able to compete with the air-gun source technology. If sufficient energy output can be achieved over the whole spectrum, marine vibrators could enable the application of established encoding techniques for land seismic vibrator sources (Dean, 2014). The simultaneous source separation techniques presented in this thesis could easily be adapted for using marine vibrator sweeps instead of air-gun sequences and would still provide the discussed benefits. Whereas marine vibrators are monopole sources, Meier et al. (2015) discuss the theoretical concept of a marine dipole source and show how its technical realization could help to overcome the ghost problem at low frequencies.

5.3.2 Crosscorrelation limits of bandlimited signals

A very interesting but also challenging research question arises from the analysis of crosscorrelation limits of near-orthogonal sequences. Whereas there is extensive literature on the concept of sequence orthogonality for binary sequences that are widely used in communication systems (e.g. Fan and Darnell, 1996; Golomb and Gong, 2005), there is hardly any literature on the orthogonality of bandlimited signals. Welch (1974) established lower limits on how small the crosscorrelation and the autocorrelations of binary sequences can be at the same time. However, to our knowledge, such limits do not exist for bandlimited signals. Finding and defining lower limits of the crosscorrelation and autocorrelations of bandlimited signals would be an interesting research objective. A theory of how to compute such limits for bandlimited signals, would also enable to evaluate the quality of the orthogonality properties of the optimized air-gun firing sequences.
5.3 Future outlook: Research perspectives

5.3.3 Enhanced source encoding

Although the encoding and simultaneous source separation techniques in the previous chapters are discussed for two sources only, the techniques can be extended to include more than two sources. The separation of a larger number of simultaneous sources will benefit significantly from sequence encoding. However, the computational cost is an issue as the system of equations to be solved for the separation scales with the number of simultaneous sources.

Besides considering conventional encoding scenarios, where the firing of an air-gun sequence is followed by a certain listening time without source shooting, it is also possible to develop continuous firing techniques. One possible setting could be the acquisition with a self-simultaneous source, whose signal overlaps itself. The required continuous firing sequences could be designed in such a way that individual air-gun firing strings are orthogonal to each other, thus enabling a much denser sampling of the subsurface. Regarding the acquisition with conventional air-gun arrays, enhanced encoding techniques could be used to fire individual sub-arrays so that they are orthogonal to each other. If more than two arrays are deployed, this could also be used to create an additional level of encoding. Instead of encoding individual sub-arrays, Furthermore, one could also think of encoding and separating individual groups of air guns within an encoded air-gun array.

5.3.4 Full-wavefield acquisition & source-gradient techniques

A fundamental benefit of marine seismic source encoding techniques explored in this thesis lies within their application for generating source-gradient data. Using the encoding techniques, the monopole responses from two closely spaced seismic sources can be separated with the presented simultaneous source separation method. In addition to these monopole responses, the dipole source response from a point between these two proximal shot points can be approximated by taking the difference between the separated monopole responses (Robertsson et al., 2008b, 2012). In this way, three independent, orthogonal dipole sources or source-gradient data could be generated: a vertical dipole source, an inline dipole source and a crossline dipole source.

Since the generation of these source-gradient data relies on the subtraction of two closely-spaced, separated monopole sources, the improvement in simultaneous source separation to reduce noise or cross-talk presented in this thesis could be pivotal to ensure sufficient quality of source-gradient data. To generate all three independent dipole source data, the monopole responses from four different shot positions are
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**Figure 5.2:** Acquisition of source-gradient data with simultaneous sources. Left: Four air-gun arrays positioned so that after separation they can be used to approximate three orthogonal dipole source directions. Right: Acquisition of source-gradient data with a depth-distributed air-gun array and two horizontally offset air-gun arrays. Using the ghost-source method vertical source-gradient data can be acquired, while horizontal dipole data are approximated via combination with the separated monopole responses of the two additional simultaneous sources.

needed, which therefore requires the acquisition of four simultaneous sources as shown on the left of Figure 5.2. To generate the horizontal dipole responses, two sources are spatially offset in the inline direction and a third additional source is towed parallel to one of those sources for the crossline source-gradient generation. For the generation of the vertical dipole response, a fourth source is towed above or below one of the other three sources. Using encoding sequences that are orthogonal to each other, the respective monopole sources can be separated. If the developed ghost-source concept for depth-distributed air-gun sources is deployed, the number of simultaneous sources required to generate all four dipole responses can be reduced to three, as no additional source is required for the vertical dipole generation (illustrated on the right of Figure 5.2).

The application of source-gradient techniques addresses many long-standing, source-side problems in marine seismic acquisition (Robertsson et al., 2012). Halliday et al. (2012) suggest that monopole and spatially filtered vertical dipole source data can be combined in similar form as for receiver-side deghosting with pressure and vertical velocity measurements (Amundsen, 1993) for source-side deghosting. Halliday (2013) compares source-gradient deghosting with other source-side deghosting schemes and suggests that if the efficient acquisition of good quality vertical dipole source data is possible, the gradient approach might be the most effective deghosting method.

In addition, the availability of source-gradient data would help to address the sampling imbalance of marine seismic data between the receiver and source spacing.
(Halliday et al., 2012). The combination of monopole and horizontal source-side gradients would enable the development of source-side reconstruction methods making use of equivalent methods as discussed by Robertsson et al. (2008a) and Vassallo et al. (2010) for the receiver-side. Using such source-side interpolation techniques, the limitations of the larger shot spacing intervals imposed by the listening time could be overcome providing significant advantages in terms of subsurface illumination.

Beyond solving these bandwidth and sampling related challenges on the source-side, the acquisition of source-gradient data could also enable novel vector-acoustic imaging techniques. Combining four-component receiver data including the measurement of the pressure and the full particle velocity vector with all four possible source data (monopole and three independent dipole source configurations), this full-wavefield acquisition would measure 16-component marine seismic data. Assuming such full-wavefield data, Vasconcelos (2013) proposes a full-wavefield vector-acoustic, reverse-time imaging method. A particular benefit of this imaging method, which allows to jointly image the up-and downgoing wavefields, is its simultaneous focusing of primary, ghost and multiple energy without their prior separation in data processing.

Looking ahead in the far future, the marine seismic source encoding techniques discussed in this thesis could enable acquisition using completely independent, autonomous sources shooting into the same or several receiver networks (Berkhout, 2012; Blacquière and Berkhout, 2013). As long as it is guaranteed that the employed encoding sequences are orthogonal to each other and the crosstalk is efficiently suppressed, such an approach would significantly boost imaging quality and acquisition efficiency.

References


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