Sound and Marine Seismic Surveys

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Underwater sound has been used for over 50 years in marine geological research and exploration.

Introduction

Sound has been used as a tool for imaging geological structure on land and in water for more than 50 yrs (**Figure 1**). Compressed air sources, referred to as airguns, have been the dominant marine sound source since the 1960s (Parkes and Hatton, 1986). Whether on land or in the water, the basic principle is that the acoustic energy from the sound source is reflected and refracted by the rock layers beneath the surface back to the receivers, thereby enabling geophysicists to reconstruct an "image" of the underlying geology, in a way that is analogous to medical ultrasonic imaging (**Figure 2**).

On land, the acoustic energy comes from buried explosives or vibratory sources that are in contact with the ground, returned vibrations are received by geophones (Sheriff and Geldart, 1995). Little or no energy is transmitted to the air to be perceived as sound.

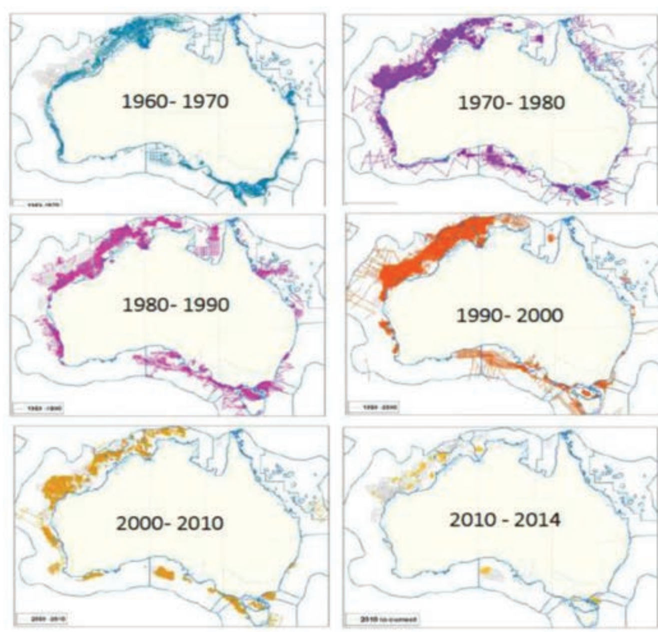

Figure 1. *A synoptic view of six decades of offshore seismic survey activity in Australia, color-coded by decade, to illustrate the extensive use of seismic surveys in oil- and gas-producing regions of the world. Box on bottom right suggests less activity, but it only covers the first four years of the current decade. From Knuckey et al. (2016), with permission from the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) and Fisheries Research and Development Corporation (FRDC).*

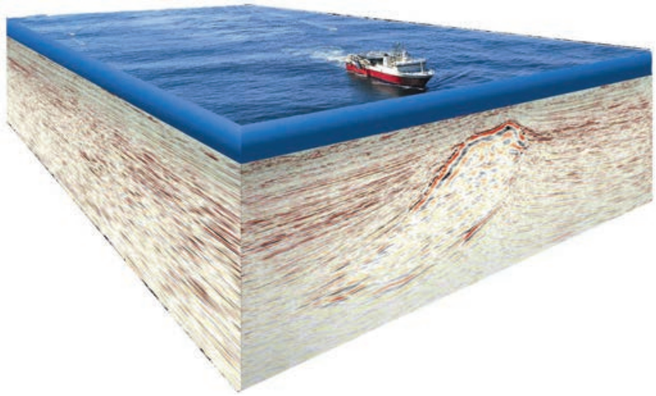

Figure 2. *Schematic diagram of a geological structure derived from acoustic survey data. The different colored bands indicate interfaces between rocks of differing density from which the geological structures can be inferred and the geology associated with faulting, volcanism, oil and gas accumulation, or other geological features of interest can be identified. Available at http://www.noia.org/wp-content/uploads/2014/01/MarineGeophysical.jpg. Accessed August 26, 2016.*

Marine seismic surveys may use energy sources on or in the seafloor (e.g., explosives, drilling noise) (Blackburn et al., 2007). The returned acoustic energy from marine inground sources is detected by geophones ("nodes") as in land surveys.

However, in many cases, water depth and the area to be surveyed dictate that towed source seismic surveys are the most practicable and economical approaches. Most marine seismic surveys, the focus of this article, involve an acoustic energy source above the seafloor, which means that sound is also radiated into the surrounding water. Use of the term "seismic testing" is a neologism coined by recent political advocacy campaigns; "seismic survey" has been consistently used historically to describe the process of collecting acoustic data for geological research.

Although most seismic surveys are associated with the discovery, exploration, and development of oil and gas, seismic surveys are also used for other purposes: harbor and ship channel engineering, geological research, earthquake and tsunami preparedness, site selection for offshore renewable energy installations (wind, tidal, and wave energy), siting of buried cables and pipelines, and support of national expanded exclusive economic zone (EEZ) claims (Canadian Broadcasting Corporation [CBC], 2016).

Marine Seismic Sound Sources

The first sound source for marine geophysical imaging was a very short acoustic pulse (milliseconds in duration) produced by an explosive. Explosives as a sound source have obvious safety and environmental concerns that led geophysicists to explore other sound sources. Consequently, compressed air sources ("airguns") are now the most widely used source of impulse sound for marine geophysical imaging (Parkes and Hatton, 1986). Electrical discharge sound sources ("sparkers" and "boomers"), water guns, various geomagnetic sensing technologies (Houghton, 2011), and multibeam sonars (International Marine Contractors Association [IMCA], 2016) are also used for marine geological surveys, but their properties and applications are beyond the scope of the current article.

Compressed air sources do not produce the ultrasonic shock wave that explosives produce and that are the source of barotrauma or "blast" injuries in animals exposed to explosives (e.g., Ketten et al., 1993). The term blast is sometimes inappropriately applied to airguns even though the air emerges at only a fraction of the speed of sound (Parkes and Hatton, 1986; R. Laws, personal communication). But then blast is not an American National Standards Institute (ANSI) or International Organization for Standardization (ISO) standardized term and has been used to describe everything from large explosions to whale sounds (e.g., Thompson et al., 1986).

Compressed Air Sources or Airguns

A typical compressed air source ("airgun") consists of two air chambers surrounding a piston/shuttle (**Figure 3**). When the pressure is equal in the two chambers, the ports are blocked by the piston. When the air from one chamber is redirected via a solenoid-activated alternative pathway, the piston is pushed out of the way, allowing the air to escape. The escaping air coalesces into a bubble, thereby generating sound by the ensuing expansions and contractions of the released bubble. The term "gun" can be misleading because there is no directed pulse of air or sound as for a piston, tonpilz, or conical speaker (Massa, 1989). Directivity is only achieved when multiple airguns are configured in an array.

The sound produced by a compressed air source is a function of the volume, size, and shape of the ports by which the air escapes and the air pressure. The amplitude of the sound increases in proportion to the cube root of the volume of the airgun, which means that doubling the amplitude (adding 6 dB of sound pressure) over that obtained from a 1,000-$in.^3$ chamber (16 L) requires an 8,000-$in.^3$ chamber (131 L) (Landrø and Amundsen, 2010). Instead of using larger airguns to achieve greater source levels, multiple smaller

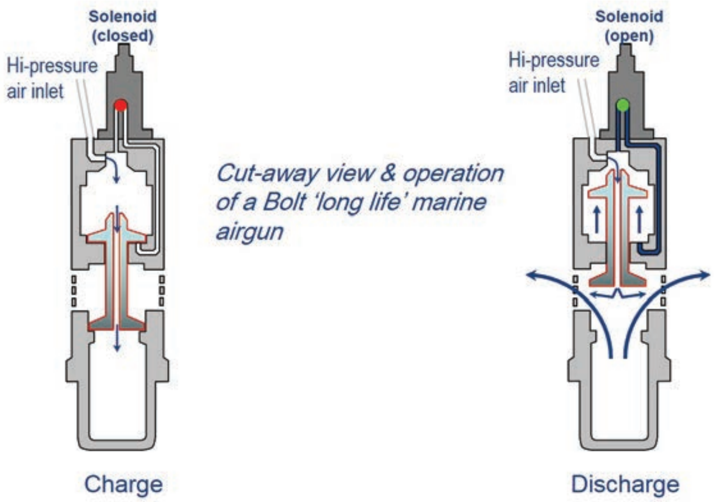

Figure 3. *Cutaway view of a compressed air sound source (airgun). See text for an explanation of source operation. From Schlumberger Ltd., with permission.*

sources are used (see **How Seismic Arrays Are Used** on page 15). Standard industry practice is to express airgun volumes, pressure, and other measures in American units like cubic inches, pounds per square inch (psi), or bars, so this review follows that convention but also gives the SI units in parentheses.

Amplitude also varies with air pressure. An air pressure of 2,000 psi (13,789.5 kPa) is most commonly used but can range from 1,500 to 3,000 psi. For reference, 3,000 psi is the typical fill pressure of a scuba tank, and 1,600-2,000 psi is the output pressure of household pressure washers.

The size and shape of the ports through which the air is released also influences the characteristics of the sound (Coste et al., 2014). In addition to the sound frequencies of interest for seismic surveys (under 100 Hz), higher frequencies are also created (Landrø et al., 2011). Minimizing acoustic energy at higher frequencies is therefore desirable from a geological imaging perspective and to reduce concerns about marine species such as dolphins, which use high-frequency sound.

Alternative Seismic Survey Sound Sources

Due to concern about the effects on marine life and to reduce source energy not used in geophysical imaging, a variety of novel sources are being explored as potential replacements for airguns (Rassenfoss, 2016). Vibroseis, a formerly trademarked name for a technology no longer in use, is often used today as a shorthand rubric for all innovative acoustic source technologies. Generally speaking, these new sources are only viable due to advances in computer signal processing, enabling a tone series several seconds long to be "reconvolved" during data processing as if all frequencies had been produced at the same time. Because the acoustic energy is spread in time, the peak amplitude is lower than that of an impulse source, but the total energy is typically comparable to that of the compressed air source. Demonstration of the anticipated environmental benefits and of the cost, reliability, and safety will likely take some time, but there is clearly widespread motivation to try to find such a source (Rassenfoss, 2016).

Arrays

Use of a single airgun for geophysical surveys is rare; more often 18-48 airguns will be arranged in a rectangular configuration: a planar array oriented parallel to the sea surface (**Figure 4**).

An array serves several purposes. First, it is the simplest way to increase the nominal level of the source, although it should be noted that the nominal source level of an array is an imaginary number, calculated by extrapolating measurements at a distance back to a hypothetical point. Actual measurable levels around the array are typically 10-20 dB sound pressure level (SPL) lower than the nominal source level in the downward direction and an additional 10-20 dB lower at increasing angles away from the vertical (Caldwell and Dragoset, 2000).

Second, the arrangement of the elements in a planar array enables the added energy of the individual elements to be directed primarily downward (**Figure 5**). At all angles outward other than straight down, there are varying degrees of frequency-dependent interference between the elements (Dragoset, 2000). This is an important point because the nominal "source level" of seismic arrays is an idealized value projected to a hypothetical point within the array. Thus a "nominal" source level of 260 dB peak SPL (SPL_{peak}; re 1 μPa at 1 m) would not produce a measurable sound pressure at that level anywhere (a fact that nonacousticians rightly find difficult and frustrating). Sophisticated modeling is, however, able to characterize the actual sound field well and is described in more detail in **Sound Propagation**.

The third and perhaps most important reason for using seismic sources in an array is the cancellation of sound from the oscillating bubbles after their initial formation. Any sound after the initial pulse clutters the return signal as well as adding high-frequency energy that is both useless for imag-

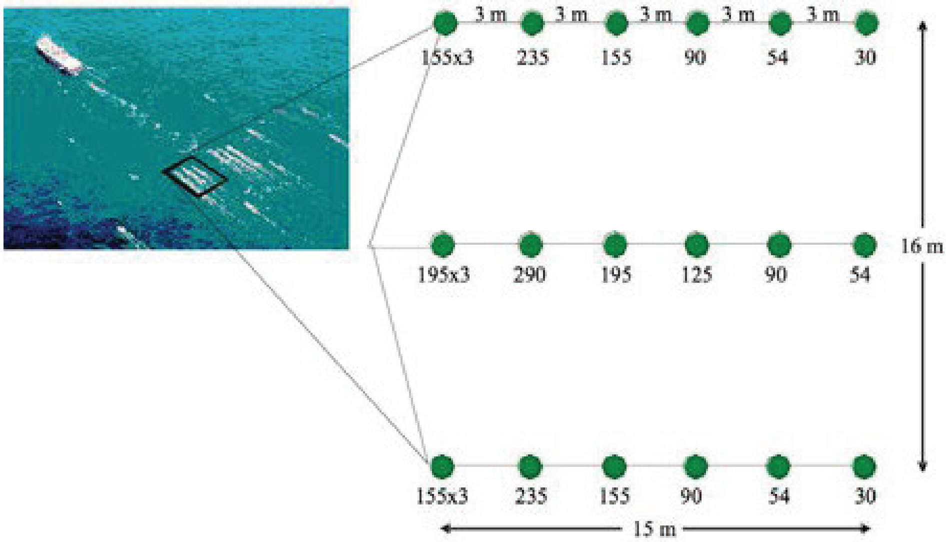

Figure 4. Relationship of the sound source arrays relative to the tow vessel. The magnified schematic representation of one of the source arrays illustrates a common combination of single and clustered elements. The number next to each dot indicates the volume of the element (airgun); numbers with a multiplier 155×3 and 195×3, indicate a cluster of airguns used to form a single larger bubble. Inset: wake of the spreaders for the receive array (streamers) can be seen to either side of the side-by-side source arrays. The streamers themselves would extend another 4-12 km behind the vessel, out of the picture. From Landrø and Amundsen (2010), with permission.

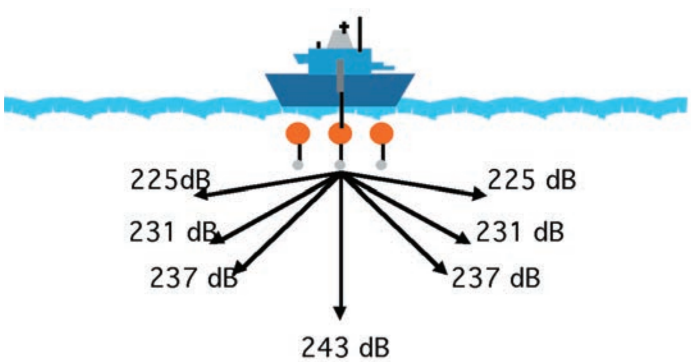

***Figure 5.** Pattern of measureable received sound levels around a schematic representation of an array (gray dots); orange dots: array floats; (not to scale). The nominal point source level of the array is 260 dB peak sound pressure level (SPL_{peak}) re 1 μPa. From Caldwell and Dragoset (2000), with permission.*

ing and potentially environmentally undesirable. By using multiple elements of different volumes, the bubbles oscillate at different rates, interfere with each other, and produce a "cleaner" pulse, as seen in the white composite waveform in **Figure 6**.

The effect of surface-reflected sound can also be seen in **Figure 6,** which shows a large underpressure immediately following the initial pressure pulse and is often referred to as the "ghost" or "ghost notch." The ghost is a time-delayed surface reflection of the pulse and thus is out-of-phase with the initial pulse due to its mirror image reflection by the surface. The surface-reflected wavefront causes frequency-specific interference patterns in the initial pulse that are a function of array depth (Caldwell and Dragoset, 2000). The depth of

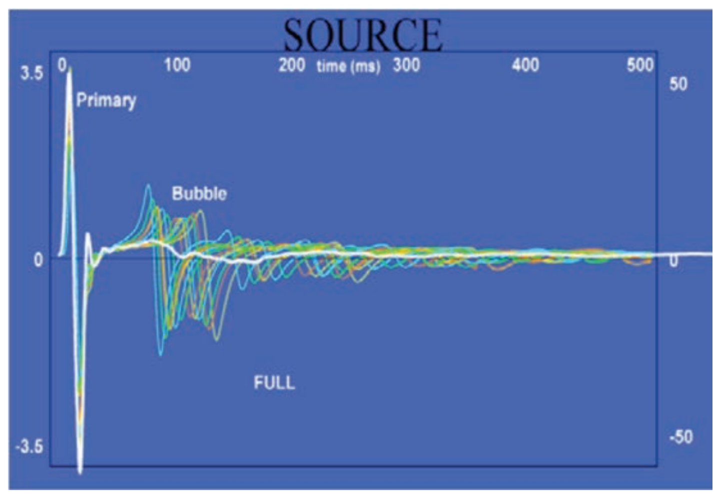

***Figure 6.** Cancellation of acoustic energy from air bubble oscillations through the use of different-sized airguns with different bubble oscillation periods. The initial large-amplitude pulse is due to the initial bubble expansion. The subsequent large negative pressure is the "ghost" or surface-reflected pulse. y-axis: Pressure relative to ambient baseline in bar-meters (left) and decibels (right). The colored lines represent what the pressure oscillations of the elements in the array would look like if the elements were activated independently. The white line represents the cancellation of sound from the varied bubble oscillations by destructive interference, producing a clean initial pulse followed by very little amplitude oscillation that would contribute additional wave fronts that would make the returned echoes messier and harder to interpret.*

the array is manipulated so that these "ghost notches" fall outside the frequency range of greatest interest for geological imaging (<100 Hz). The notch is also useful during data processing as a landmark in the return signal. Arrays are typically positioned 6 meters below the water surface to

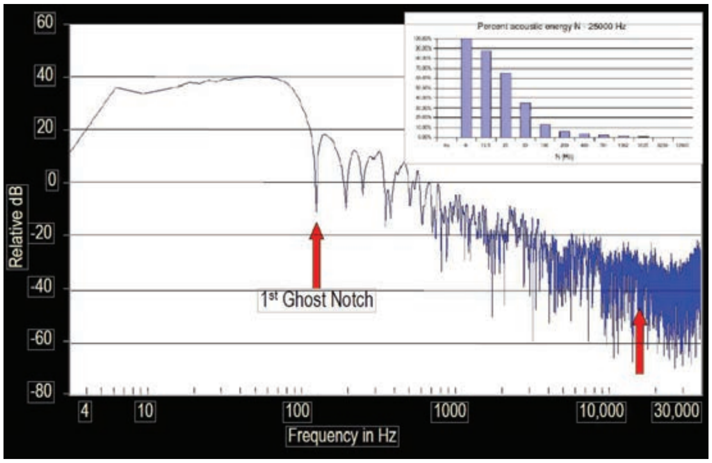

Figure 7. Frequency-transformed distribution of acoustic energy in a typical seismic array pulse such as the one illustrated in ***Figure 6****. Inset (top right): percentage of energy in each frequency band, which can be useful to readers unfamiliar with the logarithmic expressions of pressure and frequency used in acoustics. Note the effects of the "ghost notch" at 125 Hz and multiples thereof. Graphic provided by Schlumberger Ltd.*

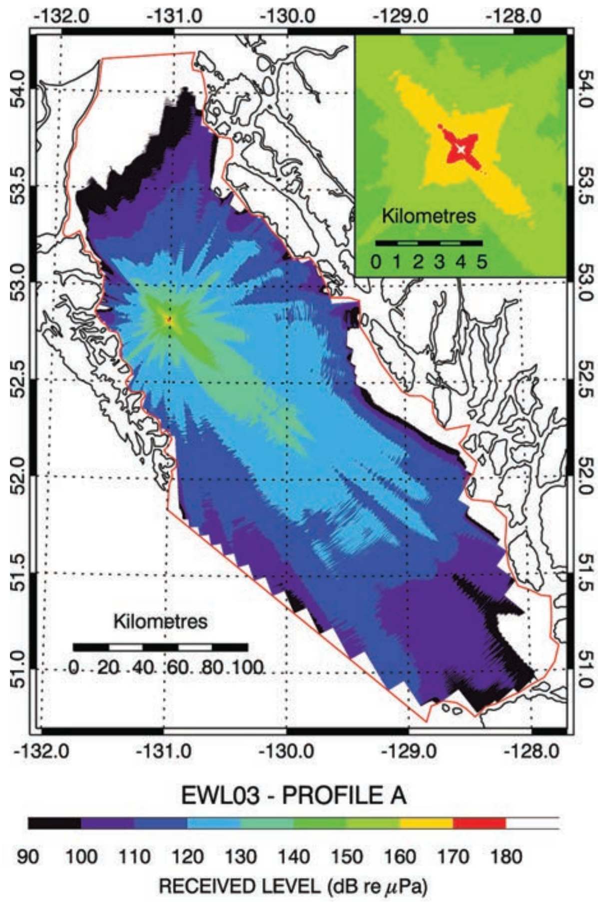

Figure 8. Irregular sound field produced by a seismic airgun array. x-axis: Latitude; y–axis: longitude. Inset: a magnified view of the field above 160 dB SPL, which is too small to see in the larger view. A similar representation of the irregular sound field generated by rectangular arrays of airguns can be found in Goertz et al. (2013). Graphical illustration from MacGillivray (2007), with permission from the Canadian Society of Exploration Geophysicists (CSEG) and the author.

place the ghost notch at 125 Hz and multiples thereof (250 Hz, 500 Hz, etc.; **Figure 7**).

Interference between the elements at every angle other than the vertical also affects the total energy and frequency structure of the received sound at different angles around the array. The lobed sound fields at different frequencies will be familiar to audiometric engineers and acousticians, but for the nonexpert, illustrations of this phenomenon in the horizontal plane can be found in BOEM (2014, vol. 3, p. D-15) and in the vertical plane in Goertz et al. (2013, Figure 4).

Sound Propagation

A high level of acoustic energy is needed to image geological structure at depths of scientific and industrial interest, typically 7 km or more. Energy lost to the water is minimal, roughly equal to the spherical spreading of the wave front over a distance equal to the water depth. Even in water depths of 2 km, the loss is small relative to the loss that occurs in the rock layers.

The sound that propagates outward in the water poses a modeling challenge and is the subject of considerable ongoing research (e.g., see the Sound and Marine Life Web site: www.soundandmarinelife.org/; also see www.DOSITS.org for a more general discussion of underwater sound). Models of the sound field near the source are well developed and are practical for good predictions of the impulse sound field out to a kilometer or so (Ziolkowski et al., 1982). Models such as Gundalf (Hatton, 2016), Nucleus (Goertz et al., 2013), or AAMS (MacGillivray, 2006) propagate the impulse in its time-amplitude form, which is computationally complex but gives an accurate representation of the pressure wave from which the frequency structure can be derived by methods like fast Fourier transform (FFT).

However, propagation over longer distances is done with computationally simpler single-frequency models developed for acoustic oceanography (Medwin and Clay, 1998). For an impulse source such as an airgun, a selected number of frequencies are individually modeled and then reassembled to generate an estimate of the received sound. Some complexity in the signal is lost in this process and it is not yet clear how significant that loss of accuracy is for assessing environmental impacts. The interference patterns of the elements in the array, together with interactions with the environment, do not generate smooth disklike patterns of outward sound propagation. A good illustration of the resulting "starlike" pattern of radiated sound can be found in MacGillivray (2007) (**Figure 8**).

The distinct impulse waveform of 0.1-0.2 s duration near the source is transformed into a series of multiple overlapping and "smeared" arrivals at a distant receiver due to environmental interactions en route. The phenomenon, from a subjective experiential perspective, is comparable to the sharp "crack" of a nearby lightning strike, compared to the "rumble" of distant thunder. These changes to the signal have very real physical and biological implications. Where is the peak amplitude of a signal that now has multiple peaks? What is the total received energy of a signal that may arrive in multiple "packets" over several seconds? What is the perceived "pitch" of the sound when different arrivals have different frequency structures?

Even for real, not modeled, received signals at distance, it can be difficult to represent these complex sounds visually. In **Figure 9**, the time-amplitude waveform in blue is identical, but the FFT time-frequency representation is different depending on the time window over which the FFT is calculated. Both biological hearing structures such as the mammalian ear and mathematical formulas for conversion of time-amplitude to frequency-amplitude (e.g., FFT) must "choose" a period of time over the pressure fluctuations are converted to a static representation of frequency or pitch. In **Figure 9, top**, the time integration window of each FFT operation is approximately 0.8 seconds, but in **Figure 9, bottom**, the time integration is closer to the typical mammalian hearing integration time of 0.2 seconds and therefore appears less smooth over time than the representation in **Figure 9, top**. Such differences in how we visually represent the frequency-converted sound wave can have significant consequences for evaluating biological phenomena such as audibility, masking, or the calculation of frequency-weighted regulatory guidelines for safe noise exposure (National Oceanographic and Atmospheric Administration [NOAA], 2016).

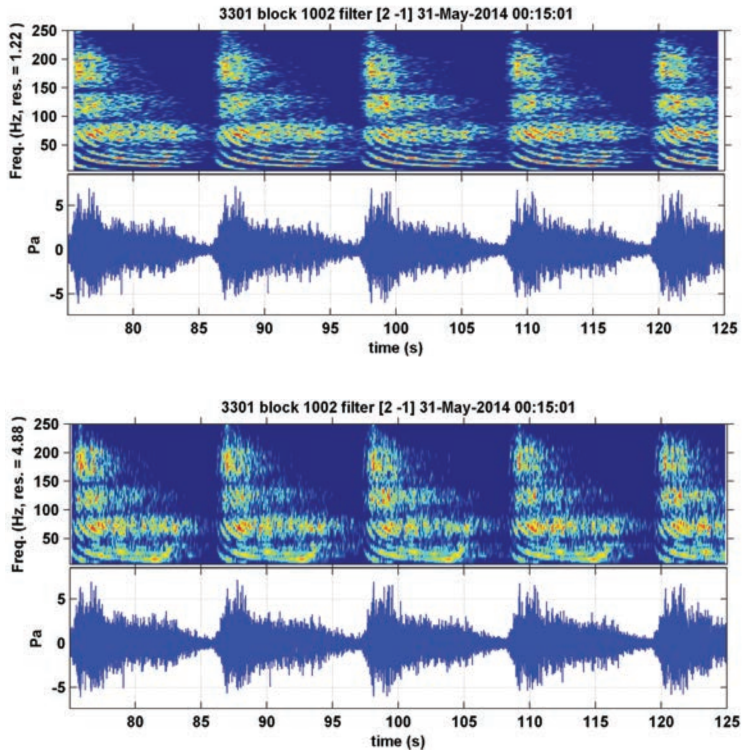

__Figure 9.__ The same received time-amplitude measurement subjected to two different frequency deconvolutions (fast Fourier transform [FFT]): at 0.8-second time windowing (top) and at 0.2-second time windowing (bottom). All other FFT parameters are the same (McCauley, 2015 and personal communication). The two different ways of representing the same signal reveal that the periods of relative loudness or quiet and the frequency structures look different depending on the way in which the time-amplitude fluctuations are translated into frequency and amplitude.

How Seismic Arrays Are Used

Towing Speed

The seismic array is towed at a constant speed around 5 knots (2.5m/s) to keep successive "snapshots" by the source array at precise time intervals, usually 10-20 s. Typically, two identical source arrays are towed side-by-side, separated by a few meters, with each array alternately activated to allow time for the other array to repressurize. A 10-s spacing between pulses (20 s for each array) puts the successive pulses 25 m apart when the ship is traveling at 2.5 m/s.

Receive Array Geometry

The receive arrays ("streamers"), like other aspects of seismic survey technology, reflect the growing capacity of computer technology to capture and process ever-larger data sets and make sense of them. A streamer is typically 4-12 km in length and might contain 300-1,000 receive modules, each of which contains a hydrophone, an accelerometer, and a depth sensor. Streamers of many kilometers in length can be significantly displaced from the axis of travel by currents, so a network of acoustic transponders ("pingers") are used to relay the actual geometry of the array to the ship's navigational displays and data-recording systems. As with many other aspects of towed seismic survey technology, the complexity of the streamer technology exceeds the limits that this short treatment can cover, but the terabytes of data streaming down the cables to the computers onboard the ship are only possible due to computer technology advances achieved in the past two or three decades.

2-Dimensional Surveys

A vessel towing a single streamer is called a 2-dimensional (2-D) survey. It produces widely spaced downward-looking "lines" that generate a coarse picture of the underlying geology. Such surveys typically range over large areas of hundreds of kilometers on a side, although this is not always the case. The spacing between lines is typically several kilometers (e.g., 4, 10, or 20 km between survey lines). **Figure 10** illustrates the mix of coarser scale 2-D survey lines and smaller areas of more tightly spaced 3-dimensional (3-D) survey lines typical of active oil and gas fields.

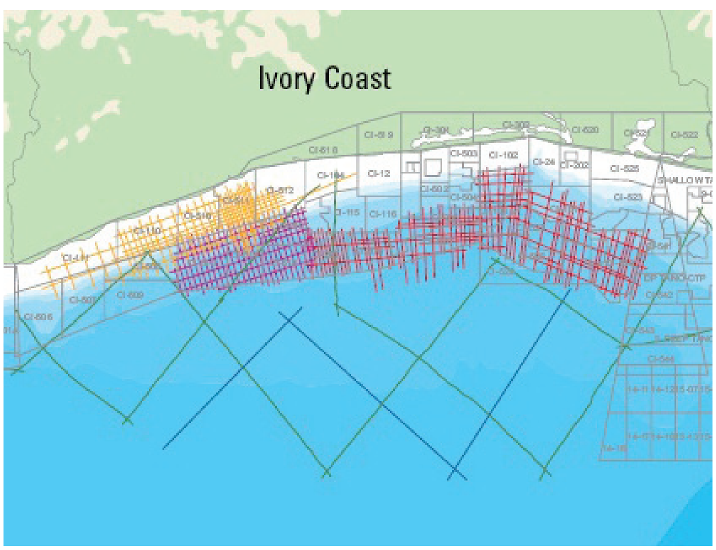

Figure 10. *Seismic survey lines conducted over several years off the west coast of Africa. The longer, more widely spaced lines are 2-dimensional (2-D) surveys. The smaller patches of densely spaced lines are 3-dimensional (3-D) surveys that are indicative of the geology, with the potential to contain oil or gas, or of existing fields being managed over time. Numbered grid: lease blocks on which energy companies may be invited to bid. The bid and the ensuing revenues to the owner state are based in no small part on the strength of the seismic survey data.*

3-Dimensional Surveys

A vessel towing multiple streamers is called a 3-D survey. In this case, several parallel streamers are towed, each typically separated by 100-500 m. The full footprint of the receive array can be as much as 6 by 12 km (Hambling, 2016). The cost of the larger towed array is offset (the operator hopes) by the reduction in survey time, which also reduces the sound put into the marine environment.

The 3-D receive array enables imaging of geology overlain by more acoustically opaque structures like salt domes and dense basalt. This "look under the edges" can be expanded with wide azimuth (WAZ) surveys, radial azimuth (RAZ) surveys, and other techniques involving one or more sound source vessels and two or more additional vessels towing only receiving arrays (Long et al., 2006).

Although the ideal survey would operate continuously for the duration of the planned survey track, in reality the source array is silent for some fraction (up to 20-30%) of the planned track lines for equipment repairs and for protected species mitigations. Depending on the amount of lost survey data, a variable amount of effort is needed after completion of the initial survey tracks to go back and fill gaps.

Maneuvering an array of large dimensions requires considerable space and time. The turning radius of a 10- to 12-km streamer for 2-D or 3-D might be 10 or 12 km and a turn might take up to 8 h, whereas a shorter streamer (i.e., 6 km) might be able to turn in 3 h with a tighter turn radius (P. Seidel, personal communication). Two-dimensional surveys, with their large line spacing of several kilometers, will usually perform a simple down-and-back pattern, whereas 3-D surveys will usually perform a racetrack or "Zamboni" pattern of overlapping loops because the lines are too closely spaced to allow for simple U-shaped turns between adjacent survey lines. During turns, the array is usually shut down; sometimes, one small airgun is operated to verify system functionality and sometimes, it is used as a mitigation measure to keep animals aware of, and away from, the array while it is turned off (the efficacy of this mitigation measure is not known, however).

Back-filling gaps in the survey lines will also differ by the survey type. A 2-D survey might simply circle back around to complete the missed segment. More often, the gaps are filled by a complex postsurvey course, with the most efficient track to fill gaps having been calculated by sophisticated navigation software.

Seismic surveys are not only used during the exploration for oil and gas but are also used throughout the life span of a producing oil or gas field. The term 4-dimensional (4-D) surveys refer to repeated 3-D surveys conducted at intervals of months or years to check the progress in tapping oil or gas deposits during the productive life of a deposit, which may last for 30 yr or more. Some 4-D survey effort may be replaced by installing fixed nodal receive arrays on the seafloor and using drilling noise or seafloor vibrational sources instead of towed airgun arrays (Blackburn et al., 2007).

Summary

Marine geophysical surveys using compressed air sound sources (airguns) have been in widespread use for over 50 yr. The basic technology of the source and the methodology of towed array surveys has not changed significantly over that time. But advances in computer technology since the 1980s have had a tremendous impact on seismic surveys, enabling exploration of new nonimpulse sound source technologies, encouraging the collection of larger 3-D data sets that cover more area with less acoustic output, and making possible a wide range of innovative multivessel data-collection methodologies (WAZ, RAX, and others). Unfortunately, the available space cannot do justice to the equally profound change in the analysis of survey data made possible by modern supercomputing technology (Yilmaz, 2001). Mathematically, intensive signal-processing innovations have enabled old data sets to yield new information as well as shaping decisions about the collection of new data sets. Changes in business practices within the industry, such as the trend toward multiclient surveys and away from single-customer proprietary surveys (International Association of Geophysical Contractors [IAGC], 2016), also need to be understood to fully appreciate the consequences of changes to the technology and the way in which it is used. Finally, although I have presented seismic surveys mainly in the context of oil and gas exploration, it is critical to keep in mind that the same technology has always had many other applications that range from basic research about the structure of our planet to coastal disaster preparedness, renewable energy development, and mapping of national claims to expanded offshore territory (CBC, 2016).

Seismic surveys and the technologies that support them are currently experiencing an unprecedented level of public attention. It is hoped that this article will provide scientists, regulatory agencies, and the concerned public with a better understanding of the technology and its uses to inform decisions about a technology that has substantial environmental, economic, and energy policy implications.

Acknowledgments

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Biosketch

Robert (Bob) Gisiner is the International Association of Geophysical Contractors (IAGC) director of marine environmental science and biology. Before joining the IAGC, Dr. Gisiner enjoyed a 21-year career with the US Navy as a research scientist, research program manager, and environmental compliance branch head. Dr. Gisiner also served as scientific program director for the US Marine Mammal Commission from 2006 to 2010. He is a recipient of the Navy Meritorious Civilian Service Award and author or coauthor of numerous peer-reviewed scientific papers and professional presentations. He has served on several expert panels on topics in marine bioacoustics, protected species recovery, and marine ecosystem management.

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