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Air Gun Arrays: Setting the Scene for a New Era

Most 3D marine seismic surveys have either towed two source arrays (dual-source shooting) each built from three sub-arrays of air guns or three source arrays (triple-source shooting) each built from two sub-arrays of air guns, and all arrays were towed between the innermost two streamers. After describing how air guns function and operate, I discuss the ways in which the sound levels recorded from seismic sources can be used in the environmental management of surveys in sensitive areas. Array configurations to enable broadband source wavefields is considered, before I then set the scene for the next Industry Insights newsletter to discuss a variety of creative deployments of so-called ‘compact’ source arrays. This evolution is variously being driven by a combination of environmental, survey efficiency and data quality ambitions.

Air Guns in Action

Air guns are canisters of compressed air that use a solenoid-based shuttle to release the air into the surrounding water through a series of ports around the body of the air gun. No explosives are used, but the term ‘gun’ presumably relates to the impulsive nature of the acoustic wavefield emitted—in the same manner as two hands clapping. As shown in Figure 1, several air guns of varying sizes are suspended in an ‘air gun array’ below surface floats towed behind a seismic vessel. A ‘gun umbilical’ links air compressors on the vessel to each sub-array, as well as supplying power and data telemetry. It is typical than a ‘near-field hydrophone’ (NFH) is mounted about 1 meter above each air gun (or ‘clusters’ of two equally-sized air guns mounted close to each other). The NFHs provide a local measurement of the acoustic wavefield emitted by each air gun—which varies slightly over time due to conditions around the air gun changing as the array is towed—and these measurements can also be used to detect air leaks and various other faults that may affect the robust operation of each air gun. Each air gun can be ‘fired’ independently (via electronic signals from the vessel), and the air supply can be isolated for each air gun. Operationally, the ambition is that the firing times, output pressure and output seismic waveform are as accurately controlled and repeatable as possible.

Figure 2 is a snapshot from an underwater movie taken by placing the camera just below the surface, and above the air gun array. The air produced by each air gun initially forms a somewhat spherical bubble around the vicinity of the air gun and then collapses because of the surrounding hydrostatic pressure, moving via buoyancy to the surface with a damped oscillation that rapidly decays into a benign cloud of bubbles (Figure 2, right). Most of the acoustic energy per air gun is released into the water within the first 30 milliseconds (0.03 seconds) of the air gun ports opening. A short time later, the acoustic wavefield is reflected downwards from the free surface of the ocean as the ‘source ghost wavefield’ with opposite polarity, and lagging the down-going initial source wavefield by a time directly proportional to the depth of the air gun.

Groenaas et al. (2016) show that the higher frequency content of the emitted acoustic wavefield is influenced by the ‘rise time’ of the initial bubble expansion—how quickly the air is released into the water. Accordingly, some air gun models used modified port shapes and internal mechanisms that delay the initial release of air into the water, thereby reducing higher frequency amplitudes that are typically unnecessary for seismic imaging but which overlap the frequencies that are sensitive for certain types of marine animals. Caution is necessary when configuring such air guns, however, as the rate of high frequency decay may be so rapid that higher resolution content in the shallower seismic images is irrecoverably compromised.

Parkes and Hegna (2011a) show that the lowest useful frequency content in the emitted acoustic wavefield is influenced by the bubble period—longer period has a lower ‘fundamental frequency’ and vice-versa. Although deeper air gun depth will cause the effects of the source ghost to reinforce lower frequency amplitudes, this benefit is strongly counteracted by the force of hydrostatic pressure. Modern ‘broadband’ signal processing attempts to remove all free-surface ‘ghost’ effects, so the towing depth becomes the critical parameter. Larger air gun volume and larger firing pressure also increase bubble period, but for various operational reasons, firing pressure is typically maintained at 2000 psi, individual air gun volume is less than 300 cubic inches (4.9 liters), and towing depth is typically in the range of 5-9 meters. The most common quantitative metric used to define the source array output is the 'far-field signature' (see the next section). Seismic signal processing benefits from having a stable and known far-field signature—that becomes difficult when air guns are towed within a few meters of the surface.

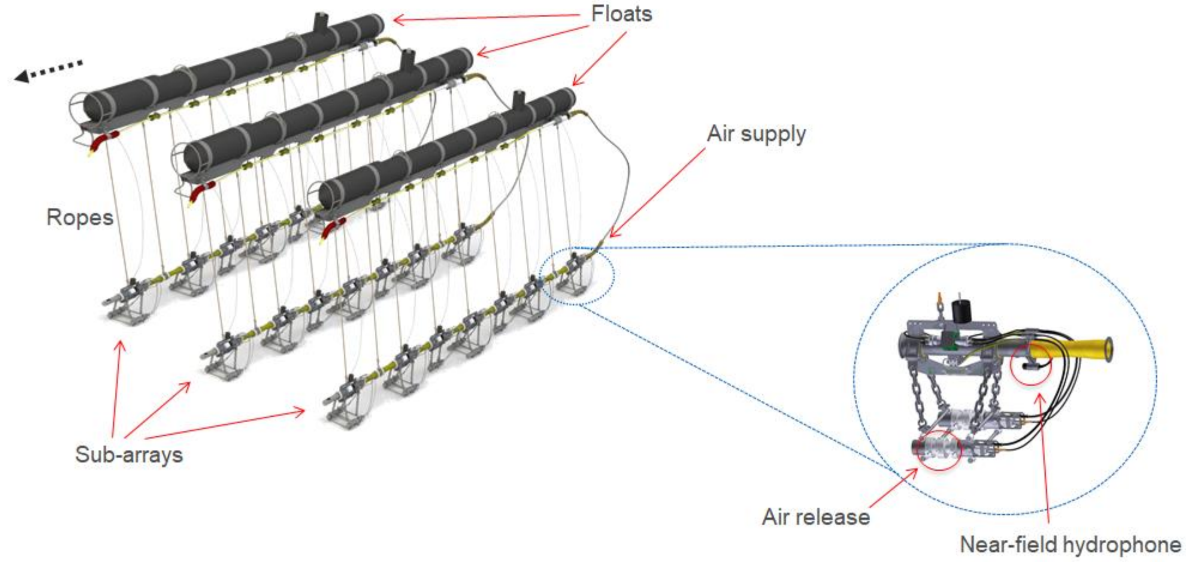

Figure 1. Schematic illustration of a source array built from three sub-arrays. Each sub-array has several air guns suspended below a surface float, and arranged as individual or pairs of air guns (clusters). A near-field hydrophone is placed at each air gun mounting location. An umbilical connects the vessel (to the left of the page) to each sub-array, and provides air, power and data telemetry.

Figure 2. Underwater photo of several air guns being fired. More than 99% of the emitted energy is released within the first 30 milliseconds, with the initial bubble radius being less than 0.5 meters. Thereafter, the air dissipates towards the surface as a benign bubble cloud (right).

How do We Define the Sound Levels from Air Guns?

The most common acoustic metrics used to describe acoustic signals in the marine environment are the sound pressure level (SPL) and the sound exposure level (SEL). The 'peak SPL' is computed using the maximum pressure p_{max} from an acoustic source (e.g. an air gun) over a specified frequency range, and stated in units of decibels (dB), with the reference pressure p_0 being 1 micropascal (1 µPa) at a distance of 1 m from the source:

$$\text{pSPL} = 10 \log_{10}\left(\frac{p_{max}^2}{p_0^2}\right) = 20 \log_{10}\left(\frac{p_{max}}{p_0}\right)$$

For example, if an air gun has a peak pressure level of 3 bar at 1 m from the air gun (1 bar = 100,000 Pa), the SPL is 20log10(3*100000/0.000001) = 229 dB.

The decibel is a 'base 10' logarithmic expression of the relative contrast between two values that is not intuitive for most people working outside the scientific community. Example relationships between amplitude ratios (A_2/A_1) and their equivalent decibel levels are as follows:

- $A_2 = A_1 \times 2$ 6 dB
- $A_2 = A_1 \times 4$ 12 dB
- $A_2 = A_1 \times 8$ 18 dB
- $A_2 = A_1 \times 10$ 20 dB
- $A_2 = A_1 \times 100$ 40 dB
- $A_2 = A_1 \times 1000$ 60 dB

The SEL is the integral of the square of the instantaneous sound pressure p(t) over some time interval T, typically 1 second (although 24 hours is another common reference interval), again stated in units of decibels, but with the reference (squared) pressure p_0^2 being 1 (μPa)^2 at 1 m from the source and T_0 = 1 second:

$$\text{SEL} = 10\log_{10}\left(\frac{\int_0^T p^2(t)dt}{p_0^2 T_0}\right)$$

Environmental Management of Marine Seismic Surveys

The received sound levels for air-gun sources are increasingly subject to threshold-based operating restrictions in terms of seasonal windows, survey exclusion areas, or marine mammal reduced power / shutdown radii from the source location as a function of the modelled source output. The frequency-dependent output from arrays of air guns can be computationally modelled with great accuracy in a three-dimensional manner (see below), so the source output may be filtered to acknowledge the frequency range of greatest (known) hearing sensitivity for specific marine animals. Then the received pSPL and SEL versus range are computed in all horizontal directions around the acoustic source. These results can be used to manage seismic operations during the survey: The acoustic output may be reduced or even halted depending upon the proximity to observed marine species or locations of commercial (i.e. fisheries) or scientific sensitivity (i.e. whale calving grounds). In some scenarios such as seismic surveys above reefs with 'site-attached' fish species or near commercial crustacean fisheries the pSPL and SEL will also be computed below the acoustic source and used to manage seismic operations as described earlier.

<u>Caution when referring to the far-field signature</u>

As noted, the most common source output metric used is the far-field signature—a theoretical description based upon the received acoustic pressure that would be recorded in an infinite body of water. The left side of Figure 3 illustrates how the far-field signature is computed (refer also to Ziolkowski et al., 1982). The emitted pressure waveform recorded by a near-field hydrophone placed one meter from an air gun / cluster is referred to as the 'near-field source signature', and can be used with appropriate mathematics to compute the 'notional source signature' for that air gun or air gun cluster. Theoretically, the notional signature is the pressure waveform of the individual air guns / clusters at a standard reference distance of 1 m from each individual air gun / cluster given the interaction from all surrounding pressure waves—from both the other air guns / clusters and the sea-surface reflections. Note that this is not something that can be physically measured. The modelled notional source from each individual air gun / cluster in Figure 3 would be individually propagated in-phase to the arbitrary reference point 9000 m below the array (1), and then summed to derive the result from all air guns acting as one 'point source'. As the rate of sound pressure decay is proportional to the distance from the air guns, the modelled far-field pressure is multiplied (or 'back-propagated') by the reference distance (9000 m) to obtain the theoretical pressure waveform at 1 m distance from the source (2): the far-field signature. As shown in the right side of Figure 3, if the pSPL at 10 m depth below was defined by linearly extrapolating the far-field pressure waveform (3), the result would be significantly higher than the pSPL that would be modelled (or recorded) by directly propagating the notional sources from each air gun / cluster location to the reference point and accounting for all constructive and destructive interaction effects. It is clear that the use of the computed far-field pSPL is entirely inappropriate when trying to describe near-field SPL around an array of air guns. Furthermore, Figure 3 shows that the far-field distance where all notional source wavefields can be considered to propagate in phase is not reached until about 200 m below the array.

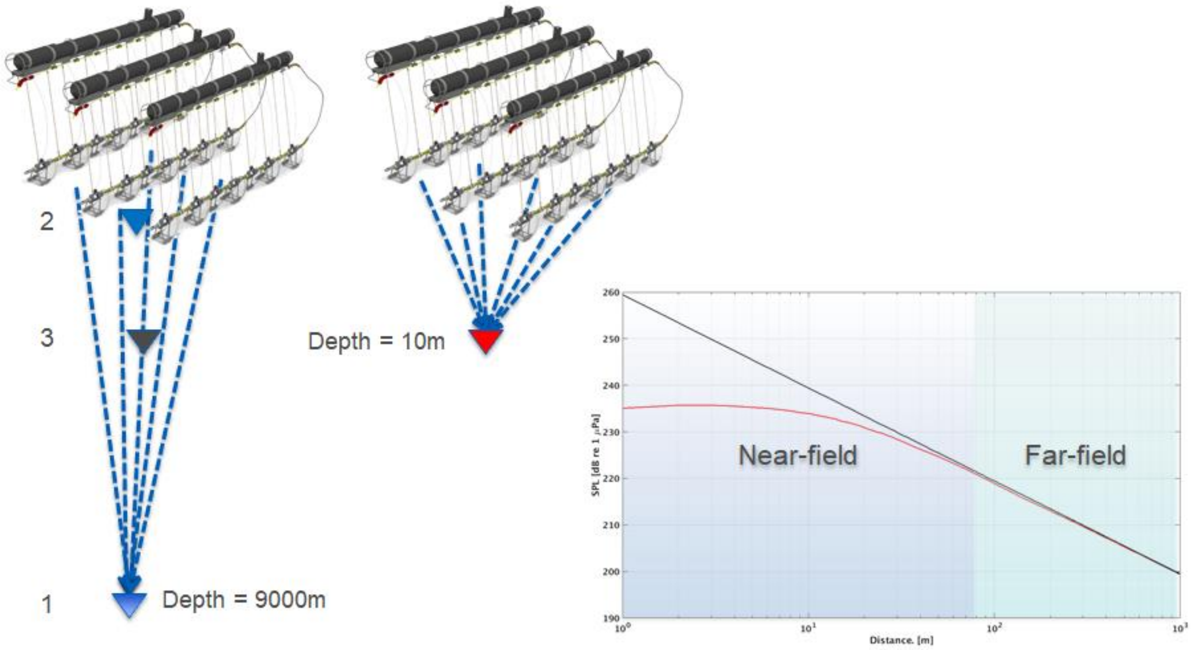

Figure 3. Comparison of how the received sound levels from a source array at a point 10 m below the array might be computed using the definition of the far-field signature (left) vs. what would actually be recorded (right). Refer to the text for details.

Source directivity

For a single gun, the wavelength of the emitted acoustic wavefield is far greater than the physical dimension of the gun, so we can consider that the 3D pressure wavefield emitted is spherically symmetric and decays uniformly in all directions. As discussed, the 3D pressure wavefield emitted from an array of single or clustered guns will not be spherically symmetric—it will vary with emission angle and azimuth.

To compute the three-dimensional emitted wavefield, the modelled notional source signatures for each gun location are used with appropriate time shifts to compute the far-field signature for every possible source emission angle (vertical propagation downwards = 0º) and source emission azimuth (horizontal propagation directly behind the source array = 0º) for the hemisphere centered on the source array. The amplitude spectra are then computed for each possible far-field signature. This enables the frequency-dependent three-dimensional source directivity to be plotted for all possible source emission angles and azimuths. Figure 4 provides an example of the modelled inline directivity. Note that any such 'directivity' correspondingly describes the *far-field directivity*—any estimates of pSPL or SEL closer than the far-field distance should be modelled using direct propagation into a 3D grid of reference points for all locations around and below the source array. The emitted source amplitudes are always strongest at zero source emission angle (vertical propagation), as are the received pSPL and SEL at all depths below the source array.

The three-dimensional directivity of any air-gun array is strongly influenced by the spatial alignment of air-gun elements in the inline and cross-line directions, as evidenced by the horizontal pSPL plot (source emission angle = 90°) in Figure 5. Note also in Figure 5 how the inline / cross-line directivity is more pronounced at higher frequencies. Consequently, the received zero-peak SPL and SEL at large ranges from the source array are highest at azimuths corresponding to the inline and cross-line directions.

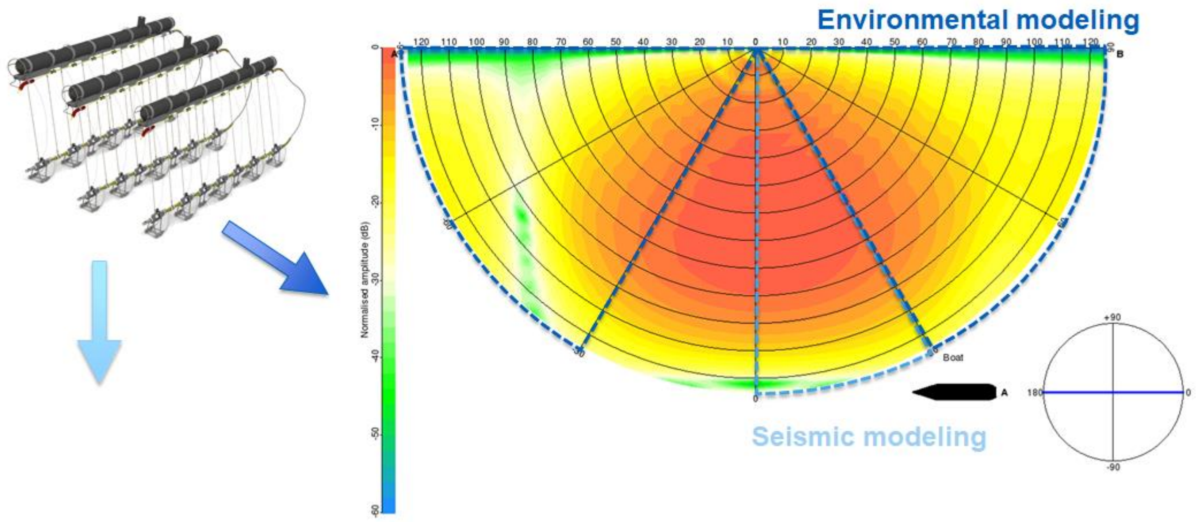

Figure 4. Modelled inline source directivity. Each radial spoke represents the source emission angle (vertical = 0°) and each arc represents constant frequency. Smaller emission angles are generally more relevant for seismic imaging, although shallow target reflections involve higher source emission angles. A spatially large array of air guns has a pronounced directivity that focuses energy directly downwards. As observed, the higher frequency content is weaker at higher source emission angles—which may be undesirable for shallow seismic imaging. High emission angles are generally more relevant to environmental modeling as the sound levels recorded in the water at both close and large range from the source array are of interest.

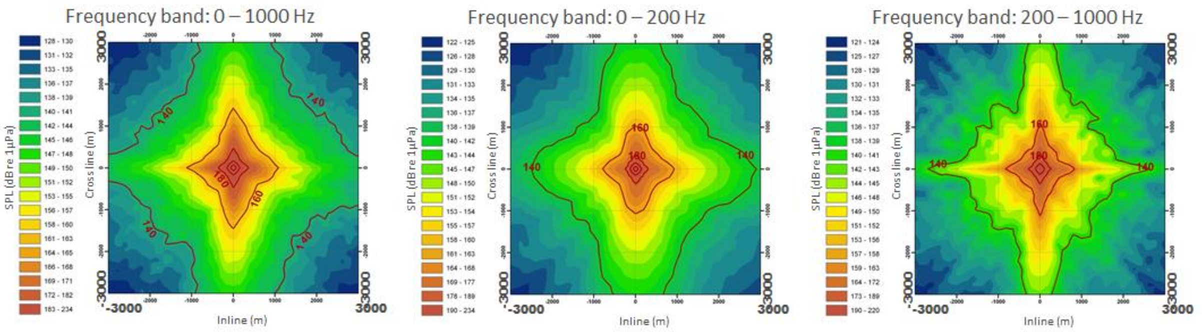

Figure 5. Azimuthal directivity plots for an array built from three sub-arrays. (left) 0-1000 Hz; (middle) 0-200 Hz; and (right) 200-1000 Hz. The vertical axis is cross-line and the horizontal axis is inline distance.

Source modeling for environmental management of seismic surveys

Environmental modeling exercises typically model the pSPL or SEL for a three-dimensional grid with either no, partial, or complete interaction with a flat, completely reflecting seafloor, assuming a simple transmission model, and possibly weighted by various acoustic weighting functions ('M-filters') associated with various species of marine mammal. Figure 6 shows the schematic workflow. The most sophisticated environmental source modelling also incorporates known geometric sound transmission effects (the rate of sound attenuation with increasing distance), seawater attenuation models, seafloor bathymetry models, and seabed geoacoustic models (if available) into the modelling of received sound levels along vertical 2D planes that intersect the water column, the seafloor, and some depth below MSL. The received sound levels can therefore be analyzed as a function of water depth and range from the source along 2D transects, or throughout a spatial region by interpolating between many azimuthal-distributed 2D transects that all intersect the same source location.

Acoustic emission characteristics are modelled for the seismic sources under consideration (e.g., specific air-gun array configurations), and then a variety of appropriate 'single pulse sites' (reference source locations), source shooting traverses, or other source deployment polygons are used in conjunction with the survey area's range-dependent properties to assess the noise exposure of marine fauna in declared sensitive locations.

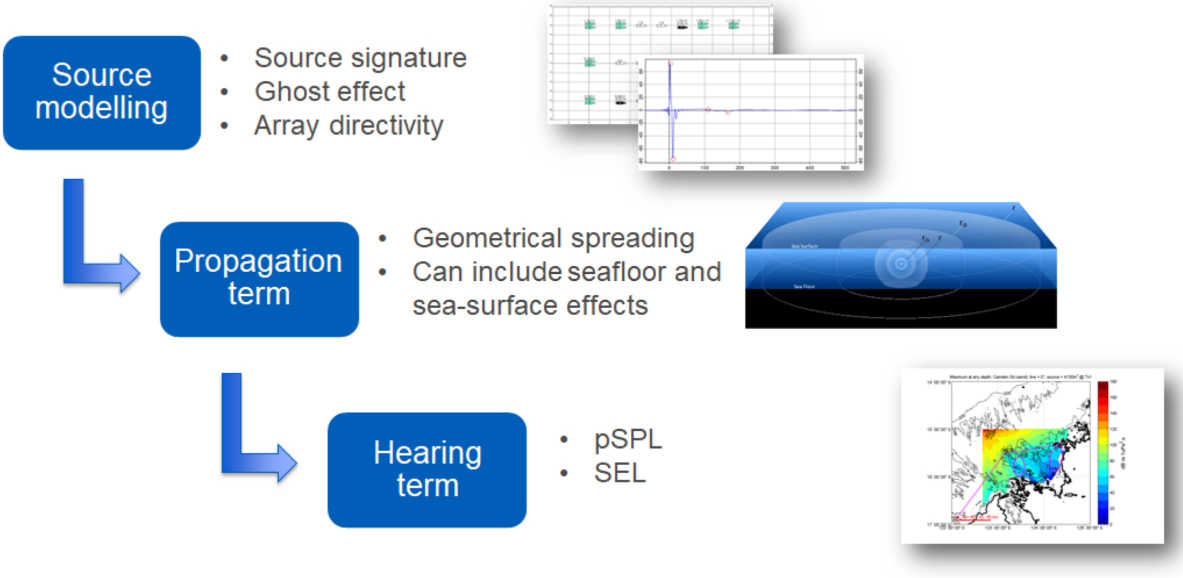

Figure 6. Schematic workflow for the modeling of received sound metrics.

Where environmental restrictions affect marine seismic activity in some region and / or during a seasonal operating window the survey commencement will typically be contingent upon demonstration that the survey execution can be operated below specific received sound metric thresholds throughout the survey area. This is achieved either by operating with the default source parameters, or by operating under range-dependent ‘low power’ or ‘shutdown’ rules—for example, when cetaceans are detected within certain distances of the source. Received sound metrics may be defined as a function of certain water depths (for example, for water depths ≤ 600 m), as a function of survey line orientation (to incorporate variations in azimuthal source directivity), for pSPL, for SEL with and without the application of M-filter auditory weighting, or for cumulative (or ‘accumulated’) SEL using either continuous or several time windows. It is typical that small-scale, site-specific sound propagation features will be blurred by wide-scale received sound modelling. In the worst-case, sound source verification (SSV) efforts may be required during the actual survey execution to verify that received sound levels are indeed within the thresholds declared by modeling, and survey mitigation efforts may be required if those received sound levels exceed the thresholds.

Calibrating and Measuring Received Sound Levels

Near-field hydrophones (NFHs) provide a local measurement for each shot, and are increasingly used to account for slight shot-to-shot variations that can affect the fidelity of high-resolution seismic images. NFHs also validate the accuracy of source modeling, but are relevant at the point of origin for the emitted source wavefield. Although limited to locations directly behind the sources, measurement from the streamer spread can be used to quantify received sound levels at various distances. Note that most streamers use groups of sensors arranged to attenuate the direct arrivals (what we would now be attempting to measure), so the ‘receiver group array’ effect needs to be compensated for in processing. More conventionally, a variety of hydrophone logging solutions are available that can be deployed at various depths in the water column and at various fixed reference locations throughout and outside the survey area. Note that a pragmatic expectation of variations in received sound levels from various source locations is necessary if the seafloor bathymetry is highly variable and/or the seafloor and near-seafloor acoustic properties are highly variable. The use of geometric spreading factors for water-only models usually predicts the worst-case received sound levels anyway as sound absorption at the seafloor tends to attenuate the propagating acoustic wavefields.

Broadband Air Gun Sources

A decade ago, the commercialization of multisensor streamers introduced the ‘broadband seismic revolution’ to the marine seismic industry, and subsequently accelerated the development of a variety of broadband source concepts. The free-surface reflections that comprise the source ghost wavefield can be partially or wholly attenuated by deploying air guns at two or more different depths, and firing the air guns at different depths with appropriate time delays. In the simplest scenario, two source arrays of equivalent size are towed at two depths, one in front of the other, and each array is fired at appropriate times such that pairs of shots from the shallow and deep array were spatially coincident. Appropriate signal processing of such ‘over-under’ data reduced the source ghost effects (Egan et al., 2007), but the decision to treat each source event as independent and with no overlap between consecutive shots (no ‘blending’) resulted in the CMP fold being halved by comparison to the nominal CMP fold for traditional shooting, and the pre-stack common offset, midpoint and receiver gathers also had the trace interval doubled—thereby compromising the higher frequencies sensitive to spatial aliasing. Hegna and Parkes (2011b) introduced a blended shooting variation to over-under shooting wherein the shallow and deep arrays (now built from one or two sub-arrays, with a total of three sub-arrays allocated to each source in dual-source shooting mode) were fired in essentially the same spatial location—so CMP fold and inline spatial sampling is not compromised. Cambois et al. (2009) alternatively describe a ‘multi-level’ approach wherein a similar deployment of sub-arrays at different depths to Hegna and Parkes (2011b) is used, but the firing times of the different depths cascade downwards at time intervals designed to constructively reinforce the down-going ghost-free wavefield and destructively attenuate the time-delayed source ghost wavefield.

When triple-source shooting gained in popularity again the use of the ascribed broadband source configurations declined in popularity—influenced also by the maturity of processing-based solutions that robustly remove source ghost effects. It also follows that if three sources are being used, a broadband source design must deploy three sub-arrays at one depth and the other three sub-arrays at another depth—using the assumption that the vessel has six available sub-arrays. There is no elegant way to similarly configure equivalent broadband quad-source, penta-source or hexa-source designs.

Downsizing is the New Trend

As I will discuss in the next Industry Insights newsletter, smaller source arrays built from two or one sub-array, or using only one air gun fired at a time have become increasingly popular in recent years for a variety of reasons. So-called ‘compact’ air gun source concepts offer a practical solution to mitigate the environmental impact of received sound levels during marine seismic surveys, as well as creating opportunities to tow sources in flexible ways that can improve survey efficiency and improve seismic image quality.

Such ambitions are not new. For example, Ramsden et al. (2005) followed the 2D symmetric sampling principles of Vermeer (1998) to design a high-resolution 3D marine seismic survey that replicated the vertical resolution of an existing 2D site survey. A dimensionally compact source array with a volume of 1400 in^3 was built from two sub-arrays towed at only 5-meter separation, and several air guns were switched off on each sub-array so that the array length was reduced from 13 to 7 meters. Consequently, 3D source directivity was minimized for high source emission angles—with demonstrable improvement in high frequency content at shallow targets. On the negative side, 4-meter source and streamer depth was used so that the respective source and receiver ghosts would reinforce the desired high frequency content—with the penalty of degraded low frequency content. This survey was acquired before the modern growth in robust processing-based deghosting solutions, and the data were unfit for pre-stack elastic impedance inversion. A contemporary version of this survey would tow a multisensor streamer spread at much larger depth (enabling complete receiver-side ghost removal), and the source array would also be towed somewhat deeper.

More recently, the main driver to use less sub-arrays per source has been the growth in acquisition with between three and six sources deployed between the two innermost streamers. As most seismic vessels carry six sub-arrays it follows that surveys using three to five sources will use arrays built from one or two sub-arrays of air guns fired together, and surveys using six sources will use each sub-array of air guns as a standalone array. The exception is continuous shooting and recording with individual air guns—as will be discussed next time.

Towed marine vibrators are an alternative seismic source concept that typically combine two or more acoustic units with complementary frequency output to roughly replicate the emitted acoustic wavefield frequency bandwidth of typical air gun arrays—albeit with much lower pSPL and SEL than traditional air gun arrays. 3D directivity effects are equally applicable to source arrays built from several marine vibrator units, and care must be taken when considering potential environmental impacts in sensitive regions.

From a survey efficiency perspective, compact sources may be somewhat more easily deployed with larger lateral source separation, with negative offsets (sources behind the first receivers of each streamer), and in combinations of different depths (to improve the emitted frequency bandwidth).

Summary

Air gun arrays are a highly mature marine seismic source concept wherein the physics is well understood, and the emitted three-dimensional acoustic wavefield can be accurately modelled. Some of the nomenclature used can be confusing—for example, the relevance of the far-field signature description—and I attempted to illustrate some key elements necessary to describe received sound levels. This is the necessary foundation for any kind of transparent dialogue with any stakeholder interested in the environmental management of seismic operations.

I also described how source array configurations are generally limited to the availability of six sub-arrays of air guns on each vessel. This restriction has influenced the design and operation of broadband source concepts, and is relevant when considering the effects of source directivity in various scenarios.

In the next edition of Industry Insights, I will profile the diverse marine seismic source concepts promoted in the last two years. Sources are now being towed outside the innermost two streamers, are towed behind the front of the streamers, include a variety of marine vibrator concepts, use a variety of air gun and marine vibrator designs to emphasize ultra-low frequency output for strategic signal processing applications, and also may involve a new paradigm of treating all seismic data as one continuous dataset rather than a sequential set of many thousands of independent records. In all scenarios, competing priorities of environmental sensitivity, operational efficiency and seismic imaging ambitions will determine the preferred source solution used.

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