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Tiny Marine Seismic Sources, Ultra-Low Frequencies, the Environment, and More

Last month I addressed the topic of Air Gun Sources—in particular the background issues necessary to describe the received sound levels for the environmental management of marine seismic surveys. I also discussed a few broadband air gun source concepts wherein the source array configurations are limited by the (typical) availability of six sub-arrays on each vessel. Therefore, dual-source shooting implies that arrays are built from at most three sub-arrays; triple-source shooting implies that arrays are built from at most two sub-arrays, and so on.

In this edition, I begin by considering new source designs wherein the sources are towed with larger lateral source separation. This leads to each source naturally comprising one sub-array of air guns. If we want to achieve the ambition of 'dispersed sources' wherein the streamer spread is surrounded by a flotilla of small sources we must also develop cost-effective and operationally-robust source vessel concepts—no easy task. I then compare various compact source concepts in terms of their three-dimensional pSPL and SEL. Some surprising results suggest that one sub-array may not be much different to several sub-arrays in terms of received sound levels. New Zealand now has one of the strictest regulatory regimes for air gun operations, and I use that as a template to suggest how 'compact' sources could be defined in an environmental context.

While we are on the topic of autonomous source concepts that are physically decoupled from the streamer vessel, I consider the pursuit of ultra-low frequencies as the primary survey ambition. Attention so far has been on either large marine vibrators or large air guns fired with low pressure as the industry dogma is that conventional air gun arrays have fundamentally deficient output below about 6-7 Hz. I briefly revisit this topic and then introduce another surprising result wherein substantial amplitudes may be recorded in the 1-2 Hz frequency range when single air guns are continuously activated and recorded in a particular manner. Collectively, the notion of 'compact' sources suggests that point sources, whether impulsive or electromechanical in nature, provide several intriguing opportunities.

Laterally Separated Sources

Figure 1 shows a typical air gun source array built from three sub-arrays. In the PGS case, each sub-array has a steering device that can independently steer each sub-array and therefore, steer the entire array to pre-plotted source trajectories. The upper-left panel shows superimposed fair-field source wavelets modelled for the entire array vs. three individual air guns of differing volume. The bubble period is different for each individual air gun, and the practice of 'array tuning' is well established wherein a variety of air guns are configured in the manner shown in the lower part of Figure 1 to collectively improve the Peak-to-Bubble ratio. The acoustic energy focused downwards (the direction relevant to seismic imaging of the subsurface) approximates a short impulse. The related aspect of three-dimensional 'directivity', and the concepts of 'near-field' vs. 'far-field' acoustic wavefield propagation were discussed in the previous newsletter.

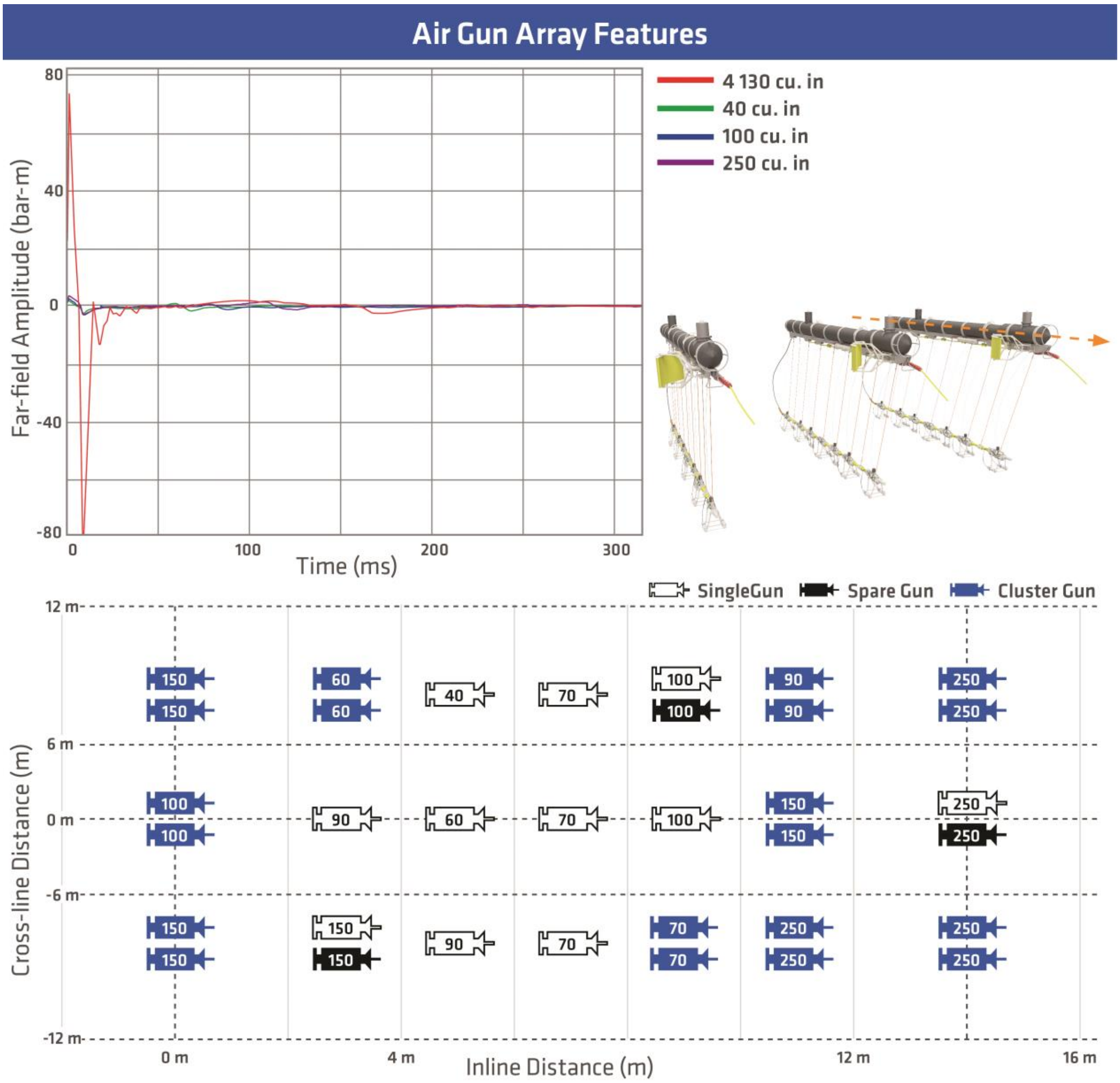

Figure 1. (upper left) Superimposed far-field signatures for the 4130 cubic inch source array (lower panel) and for three individual air guns; (upper right) Three-dimensional source array perspective, with the vessel sailing out of the page; and (lower) Spatial air gun configuration. In a standard source array three 'sub-arrays' of air guns are suspended at a fixed depth below surface floats. Each sub-array contains various single gun placements as well as clusters of two guns. Some clusters use an inactive 'spare' gun during normal operations.

Figure 2 shows a generic configuration of two source arrays towed between the two innermost streamers in a multi-streamer configuration. Using the nomenclature of a common midpoint (CMP) occurring mid-way between every possible source and receiver surface coordinate, several CMP sublines are defined for the vessel configuration where (number of sublines) = (number of sources) x (number of streamers), and the 'near offset' for each subline is the minimum distance between the respective source and streamer that contribute that that subline. Figure 1 illustrates an example relationship between streamer 1 and source 1 that has CMPs with different source-receiver offsets distributed along subline 1. Long (2017) demonstrates that geometric relationships can be found between the streamer separation L, the number of streamers N, the number of sources S, an integer k than is zero for the conventional deployment of sources between the innermost two streamers (increasing values of k correspond to the outermost two sources in a dual-source or triple-source configuration being placed outside the innermost two streamers with increasingly large lateral separation), and the following parameters:

Source Separation	$L\left(k + \frac{1}{S}\right)$
Subline Separation	$\frac{L}{2S}$
Sail Line Separation	$\frac{L}{2}(N + k)$

Table 1. Relationships between geometric parameters for towed streamer acquisition with two or more sources. L = streamer separation, N = number of streamers, S = number of sources, k is an integer. Refer also to Figure 2.

Note these relationships extend to higher numbers of sources being used too (see below), but I restrict the initial discussion here to dual-source shooting. For the example in Figure 2 where the number of streamers N = 10, the number of sources S = 2, and k = 0, a streamer separation of L = 100 m would have nominal source separation of 50 m, subline separation of 25 m, and sail line separation of 500 m.

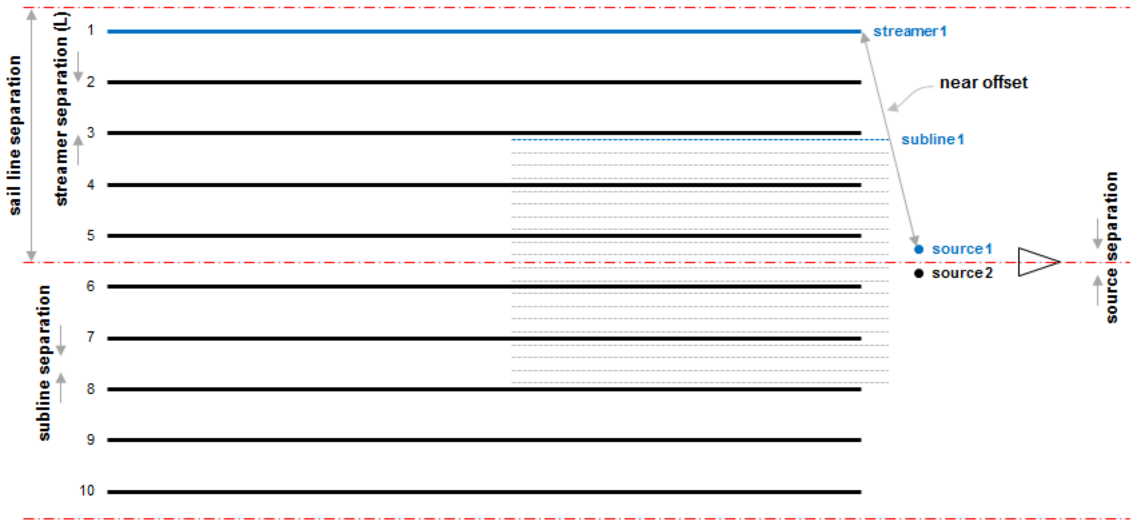

Figure 2. Nominal towed streamer acquisition geometry for dual-source shooting with 10 streamers.

As most seismic vessels carry six sub-arrays, it follows that the following multi-source configurations are possible:

- Dual-source shooting with each 'source' built from one, two or three sub-arrays (assuming the geometric center of each source is separated by L/2)
- Triple-source shooting with each 'source' built from one or two sub-arrays (assuming the geometric center of each source is separated by L/3)
- Quad-source shooting with each 'source' built from one sub-arrays (assuming the geometric center of each source is separated by L/4)
- Penta-source shooting with each 'source' built from one or two sub-arrays (assuming the geometric center of each source is separated by L/5): It has been shown that six sub-arrays evenly-separated by L/5 can be fired two-at-a time in penta-source mode
- Hexa-source shooting with each 'source' built from one sub-arrays (assuming the geometric center of each source is separated by L/6)

In each scenario here it is assumed that all 'sources' are towed between the innermost two streamers. Any array built from one or two sub-arrays is obviously more 'compact' (spatially, and probably also in terms of overall air gun volume) than an array built from three sub-arrays. Ramsden et al. (2005) and Dhelie et al. (2017, 2018b) each show that arrays (built from two sub-arrays in each case study) can be configured with various air guns switched off to make the effective source array length shorter. The three-dimensional array directivity will be closer to that of a point source—and with associated higher frequency wavefield emission for shallow target reflections—and somewhat lower received peak-sound pressure level (pSPL) and sound exposure level (SEL). It is shown below, however, that one sub-array may yield equivalent pSPL to an array built from three sub-arrays—so caution should be exercised.

Figure 3 schematically shows how the use of a larger lateral source separation can be used to increase the nominal sail line separation by a distance equal to 0.5Lk, where k increases from 1 to 2 in this example. So a 100 m increase in lateral source separation translates to an increase in nominal sail line separation of 50 m. Survey efficiency can therefore be somewhat improved—albeit with the penalty of some CMP sublines having reduced fold that must be addressed during the data processing stage. Widmaier and O'Dowd (2017) also show how increased lateral source separation will translate to a more uniform near-offset distribution for all CMP sublines—particularly as the number of sources being towed increases.

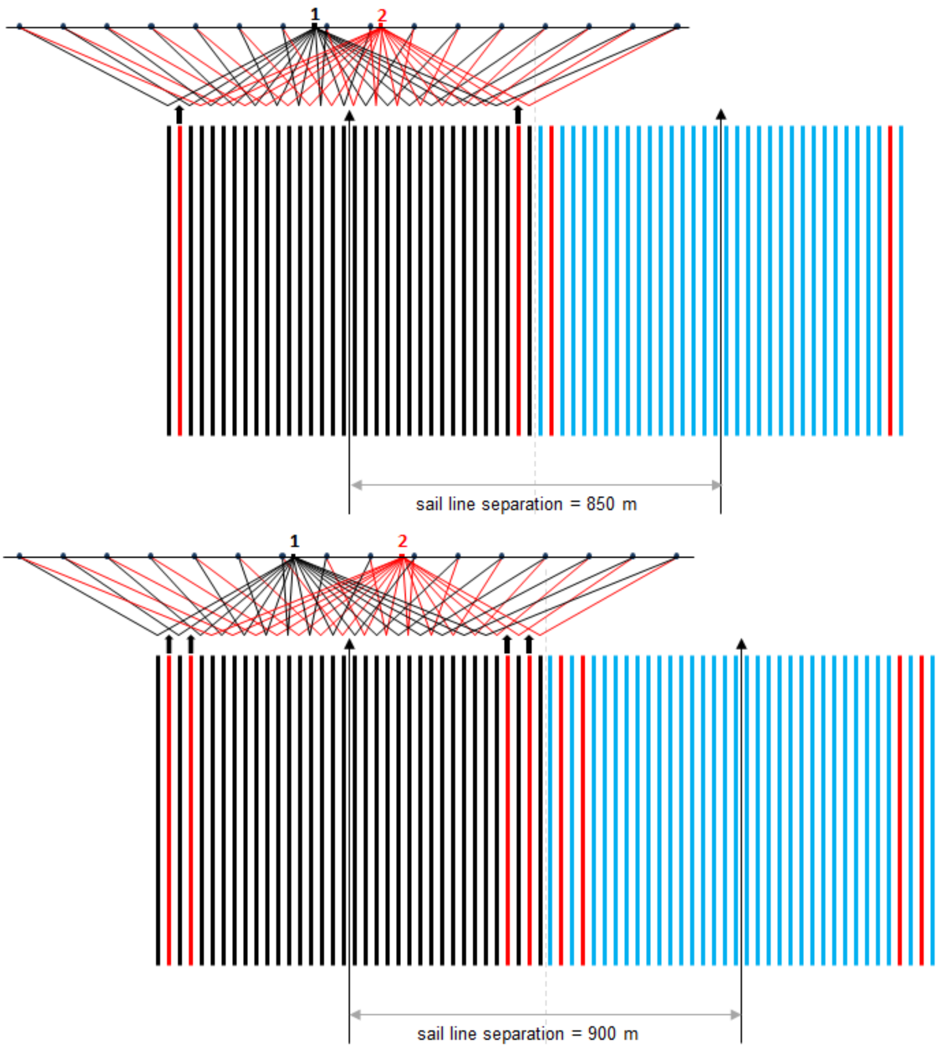

Figure 3. (upper) Cross-line ray path schematic for a wide source towing with two sources (source separation = 1.5 x streamer separation) configuration with 16 streamers and overhead perspective of the sublines for two adjacent sail lines; and (lower) Equivalent plot for source separation = 2.5 x streamer separation. Sail line 1 in both scenarios is represented by black sublines, sail line 2 is represented by blue sublines, and red represents zero fold sublines. From Long (2017).

Dhelie et al. (2018a) present a case study where the lateral source separation of six evenly separated sources (each built from one sub-array) and the nominal sail line separation were matched to allow uniform source line separation throughout the 3D test area. In this case, the lateral source separation was 60 m and the nominal sail line separation was 360 m. As intimated by Figure 3, the cross-line CMP subline fold would be non-uniform, but once addressed in processing the denser cross-line spatial sampling of the source wavefield should benefit seismic imaging quality and resolution. Figure 4 conceptually illustrates that traditional dual-source shooting results in a source line separation wherein pairs of closely separated source lines are separated by large distances roughly equal to the nominal sail line separation. In contrast, a hexa-source survey design can enable uniform source line distribution. In this example, for an 18-streamer configuration the lateral source separation is increased from L/2 to 3L/2, and the nominal sail line separation remained unchanged.

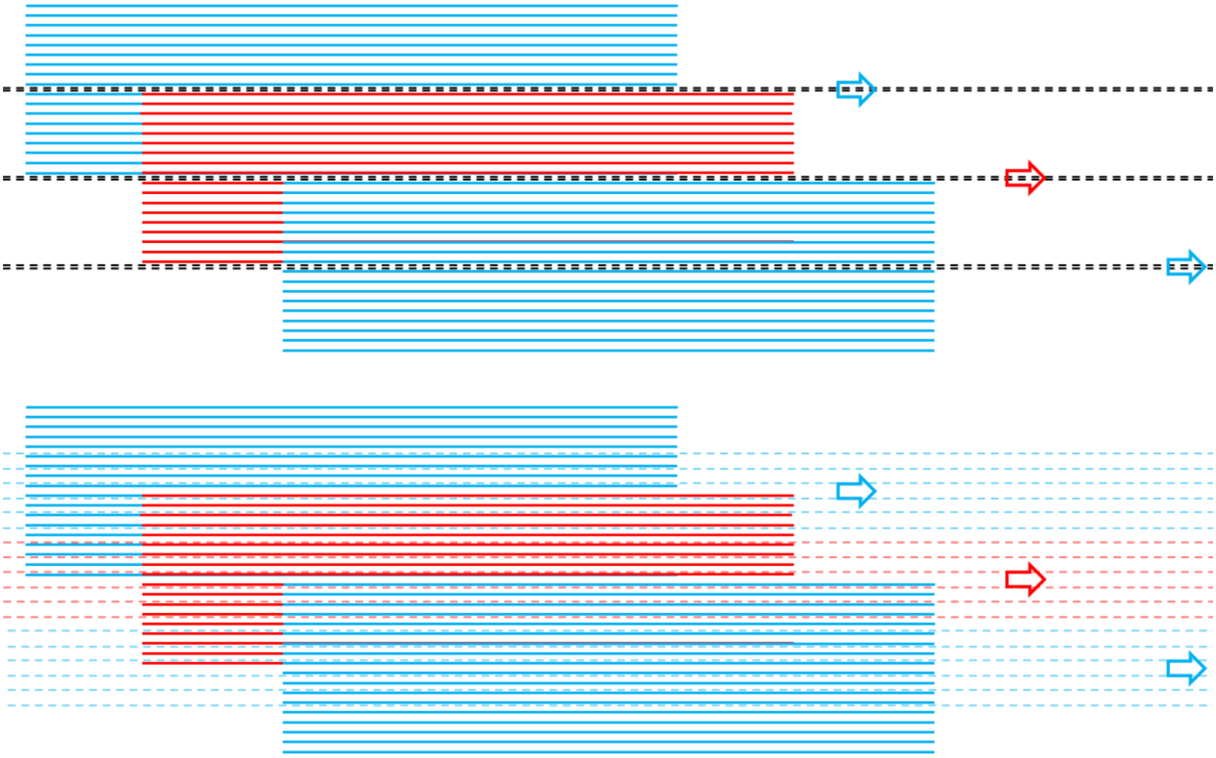

Figure 4. (upper) Schematic illustration of three adjacent sail lines wherein a vessel tows 18 streamers and a traditional dual-source shooting configuration. Each sail line produces two narrowly-separated source lines: Lateral source separation = 0.5 x streamer separation; and (lower) Schematic illustration of three adjacent sail lines with the same nominal sail line separation, but wherein the vessel tows 18 streamers and a hexa-source shooting configuration designed to produce six evenly-separated source lines: Lateral source separation = 1.5 x streamer separation in this scenario.

In practice, the ability to maintain large lateral source separation is limited by a few operational factors:

- The manner in which source separation is achieved (winches from the paravanes vs. steering devices on each sub-array)
- The length of the umbilicals connecting each sub-array to the vessel (air supply, power and data telemetry)
- Ability to recycle the air compressors on the vessel, etc.

No one has yet achieved a lateral separation greater than 300 m between the outermost two sub-arrays in practice, but this is obviously an area to watch. Next, I address the concept of 'dispersed' sources wherein independent source vessels enable the sources to be physically decoupled from the vessel towing the streamer spread.

Dispersed Source Concepts

Figure 5 is from Blacquière and Berkhout (2013), and introduces the concept of dispersed source arrays (DSAs) as the marine form of robotized or autonomous source concepts. As discussed in Berkhout and Blacquière (2012) and Berkhout (2013), each source emits a band-limited source wavefield designed to facilitate more robust separation of the interfering source wavefields in data processing ('deblending'). Caporal et al. (2015, 2016) apply this concept using simple synthetic modelling and data processing, and Chalenski et al. (2018) advocate the use of fully automated dispersed sources to improve survey efficiency.

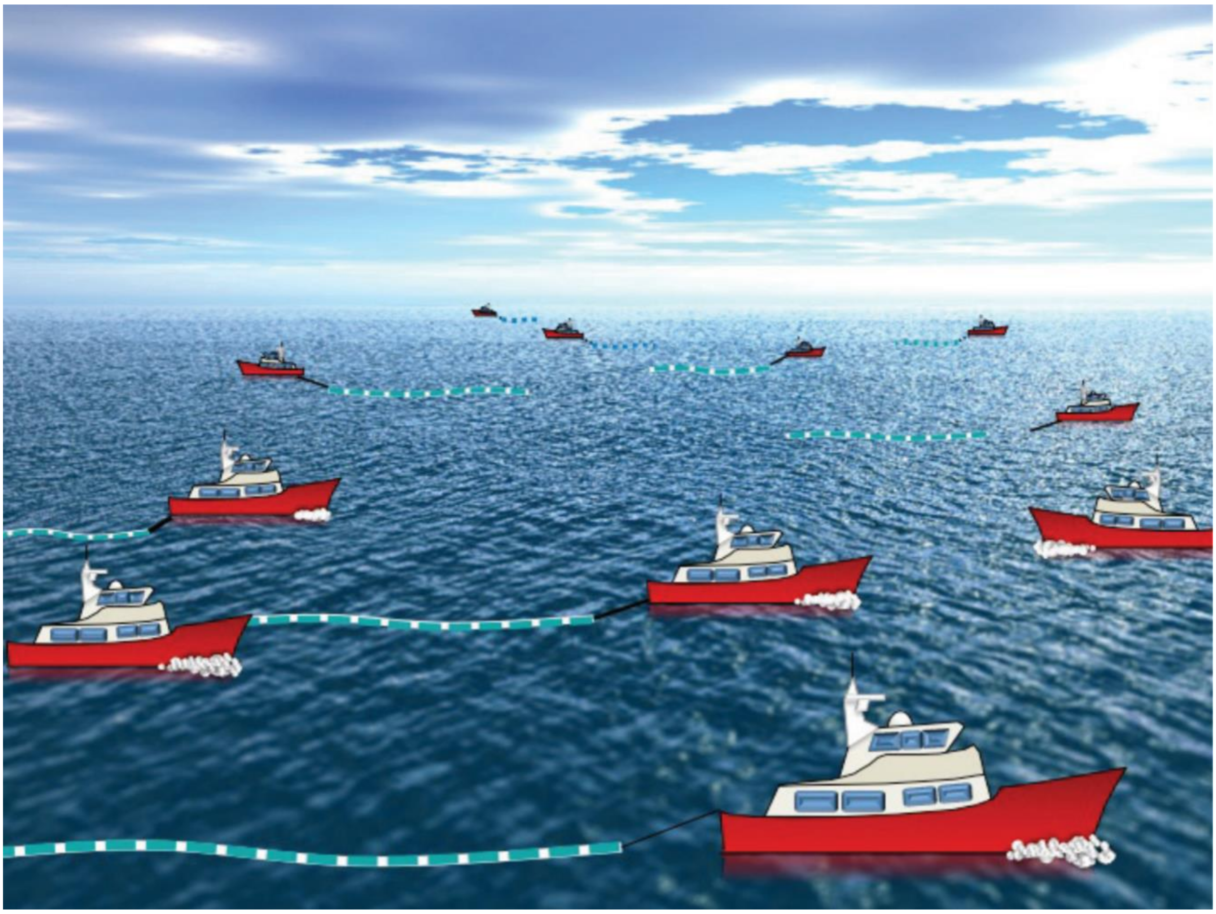

Figure 5. A conceptual number of unmanned shooting boats, each towing a simple narrow-band source, together forming a dispersed source array (DSA) and towing a short streamer. DSAs cover the full spatial and temporal bandwidth to illuminate the subsurface in an optimum way. Spatial sampling and deployment depth are source dependent. From Blacquière and Berkhout (2013), Figure 2.

Any such 'small boat' source concept will necessarily be limited to using very small air compressors for air gun operations, so any air gun arrays would correspondingly have very small volumes (probably only a few hundred cubic inches). The obvious alternative dispersed source concept that has no requirement for air compressors, could be towed from small vessels, and that can be robustly operated with a band-limited source wavefield, is towed marine vibrators (MVs). No MV solution has yet been commercialized for deep-water operations, but several MV concepts have been developed over the years (see Landrø and Amundsen, 2018; Tenghamn et al., 2018). A Joint Industry Project (JIP) run in the US has simultaneously managed several competing MV concepts (Feltham et al., 2017), but none are yet in operation. The JIP source specifications (Schostak and Jenkerson, 2015) require a broadband source wavefield comparable in output to that of a small-to-medium size air gun array. This will in practice necessitate an array of about 12 MV units—such as conceptually shown in Figure 6 wherein four low frequency (5-20 Hz) and eight higher frequency (20-100 Hz) units are towed at two depths using the flextensional MV concept of Tenghamn (2006).

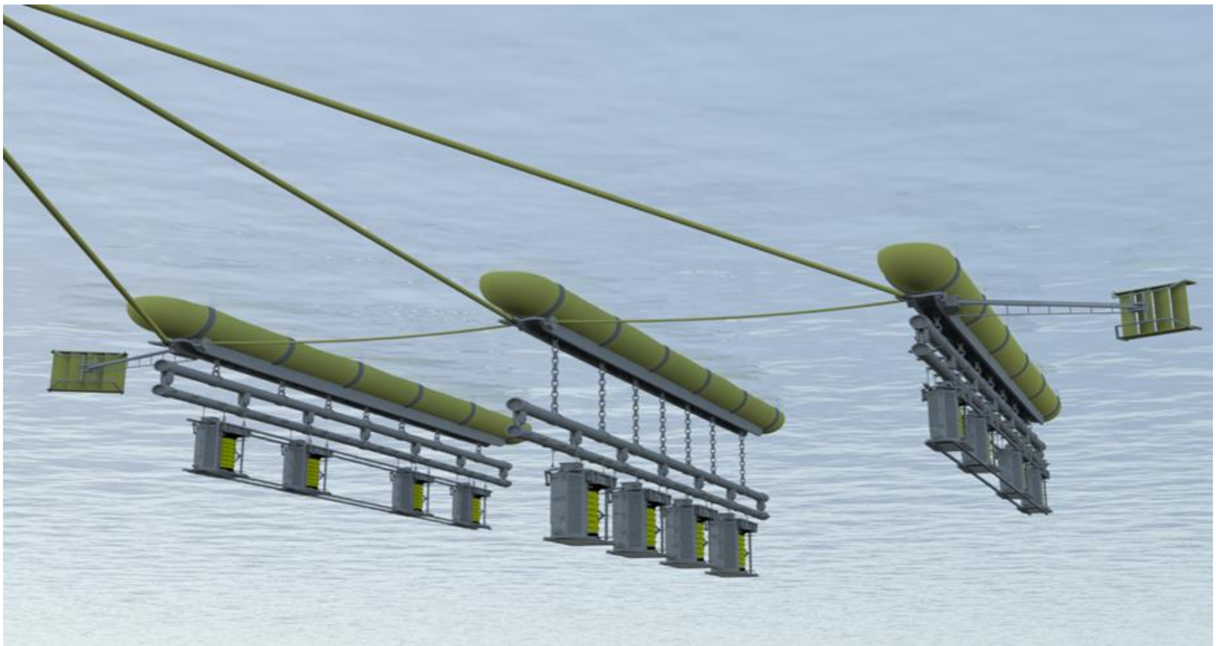

Figure 6. Conceptual array of 12 marine vibrator units using the flextensional shell concept of Tenghamn (2006).

It has been shown, however, by Pramik et al. (2015) and Mougenot et al. (2017) that a compact MV array built from only one low frequency and two higher frequency MV units based upon Tenghamn (2006) can provide comparable deep signal penetration and data quality to a medium-size air gun array in shallow water conditions. Correspondingly, Archer (2018) promoted a concept wherein 12 fully autonomous (i.e. dispersed) small vessels each towed an array of three MV units operated simultaneously (10 active and 2 refueling / in maintenance at any given time), thereby providing high rates of daily acquisition. The conceptual illustration in Figure 7 alternatively shows arrays of MVs (such as in Figure 6) being towed by the streamer vessel. Placing sources outside the streamer spread can in principle double the survey efficiency. Norris et al. (2017) also propose the concept of placing very small air gun sources within the head buoy of each streamer, and supplied by compressed air tanks placed in the buoys.

Note, however, that an array of MVs has a directional output, and this must be carefully considered from an environmental perspective—discussed below.

Revisiting pSPL / SEL for Compact Sources

Reference is made here to my discussion of pSPL and SEL in the previous newsletter.

Figure 8 is from Long et al. (2019) and is based upon components of the 4130 cubic inch source array in Figure 1. Figures 8A to 8P compare the modeled SPL and SEL for the 4130 cubic inch array built from three sub-arrays of air guns versus one of the three constituent sub-arrays, individual air guns (150 cubic inch) being activated in rapid succession, and a small towed marine vibrator (MV). The source depth in all scenarios is 6 m, and the SEL integration window in all scenarios is 10.5 seconds (the total sweep + listen duration for the MV). Modeling used the Nucleus+ software for a homogeneous medium, with semi-cylindrical spreading to account for bathymetry, and for a flat free surface. Note that the modeled MV output simulates equivalent emitted energy at all azimuths and does not replicate the azimuthal directivity that would exist in practice with an array such as shown in Figure 6. Figures 9A to 9D compare in the inline and cross-line SPL and SEL vs. distance for the four source scenarios considered in Figure 8.

For the first and third columns in Figure 8, the vertical axis in each panel is the cross-line direction, the horizontal axis in each panel is the inline (towing) direction, and both axes span a range of ± 3000 m from the source. For the second and fourth columns in Figure 8, each panel represents a vertical plane, with the vertical axis spanning a depth range of 7-450 m below MSL, and the horizontal axis spanning a range of ± 3000 m from the source.

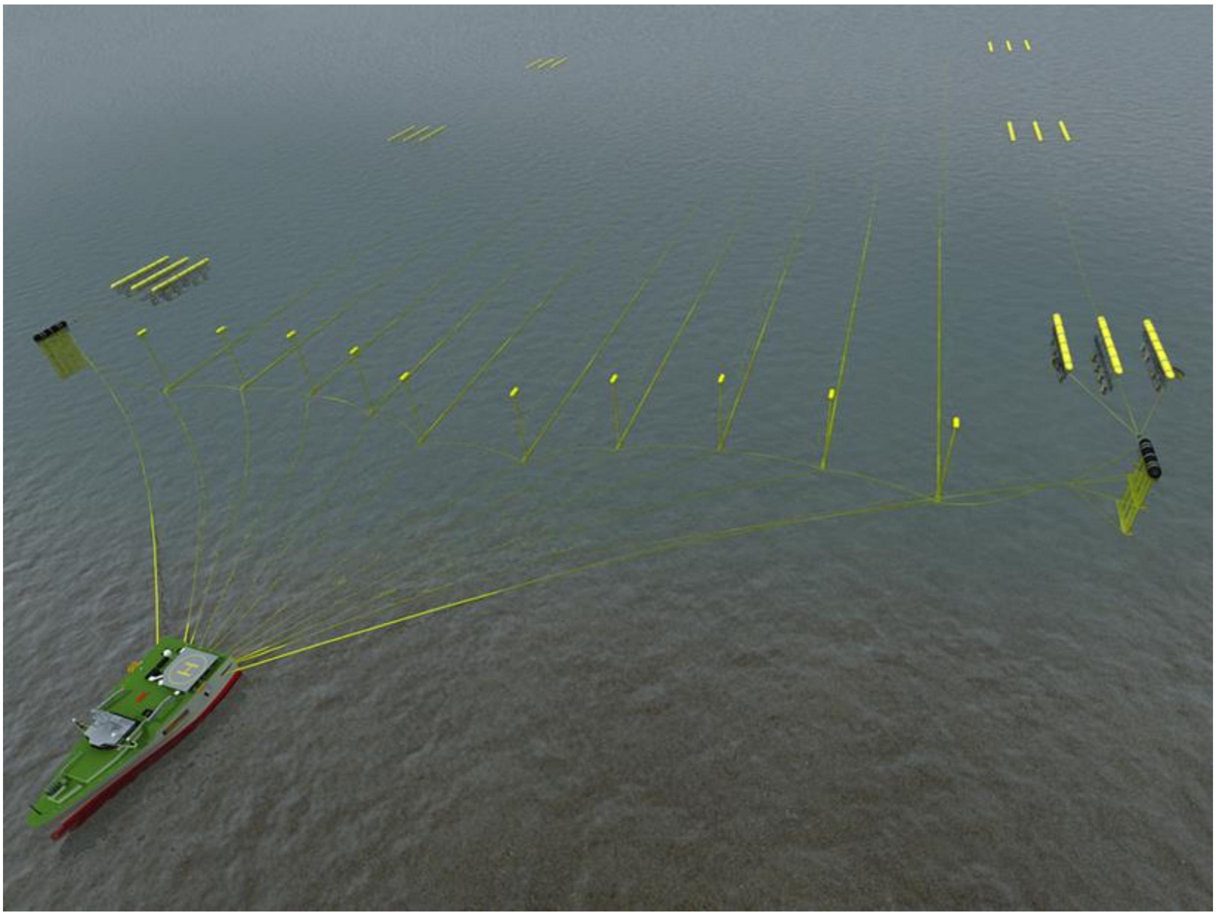

Figure 7. Conceptual towing of marine vibrator arrays by the streamer vessel. Each marine vibrator unit would have a low power and telemetry connection to the vessel, but no air supply requirement.

Note in Figures 8A and 8E how the cross-line received pSPL is essentially the same for three vs. one sub-array, respectively. This is also illustrated in Figure 9B. The explanation for this observation is due to the way that the amplitude peaks from the three sub-arrays align in the cross-line direction. The azimuthal received pSPL and SEL is highly asymmetric for both arrays of air guns (Figures 8A, 8C, 8E and 8G, respectively). Note in Figure 1 how the largest air gun clusters are typically placed in the corners of arrays. Duncan (2017) shows with modelling that the received sound levels can in fact be reduced by placing the largest air guns in the center of an array, and the smallest air guns around the perimeter of an array (refer to Figure 10). However, this is operationally undesirable as the performance of an array is most dependent upon the largest guns being active. If one air gun fails the acquisition may need to pause while the array is repaired (or a 'spare' gun is available in the appropriate location)—so it is operationally more practical to place the largest air guns on the corners of an array where they are more easily accessible for maintenance.

Figures 8I to 8P emphasize the point source nature of individual air guns and a compact marine vibrator array: Spatial dimensions considerably smaller than the seismic wavelengths of interest. Duncan et al. (2017) illustrate how the azimuthal directivity of an array of MV units is equivalent to an array of air guns, and careful consideration must be given to how such arrays are designed in environmentally sensitive locations—once such concepts are used commercially.

It is worth noting how rapidly sound levels decay in water. For each scenario shown in Figure 9, the received pSPL and SEL have reduced by more than 20 dB or 90% at a distance of 500 m with respect to the levels at the source location, and have reduced by more than 40 dB or 99% at a distance less than 1500 m from the source location. Columns 2 and 4 in Figure 8 also show how rapidly sound levels decay both vertically and laterally away from the source location. Refer also to Ronen (2002) for a short tutorial on the relationships between air gun pressure and sound levels (although the commentary on necessary sound levels for seismic imaging are now outdated—see below).

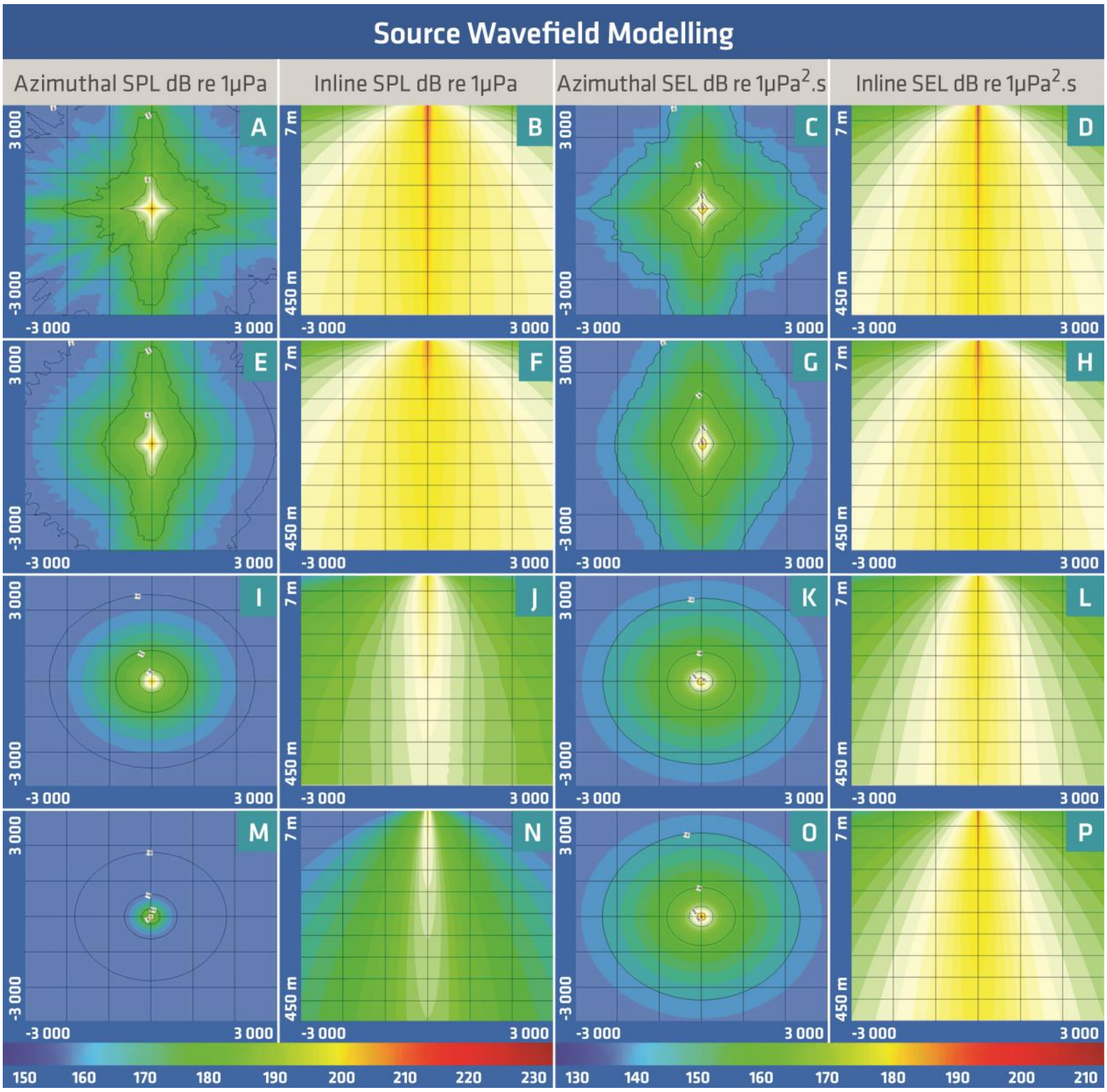

Figure 8. (A) Azimuthal received SPL for three sub-arrays of air guns; (B) Inline received SPL for three sub-arrays of air guns; (C) Azimuthal received SEL for three sub-arrays of air guns; (D) Inline received SPL for three sub-arrays of air guns; (E) Azimuthal received SPL for one sub-array of air guns; (F) Inline received SPL for one sub-array of air guns; (G) Azimuthal received SEL for one sub-array of air guns; (H) Inline received SPL for one sub-array of air guns; (I) Azimuthal received SPL for one air gun being continuously activated; (J) Inline received SPL for one air gun being continuously activated; (K) Azimuthal received SEL for one air gun being continuously activated; (L) Inline received SPL for one air gun being continuously activated; (M) Azimuthal received SPL for a towed marine vibrator; (N) Inline received SPL for a towed marine vibrator; (O) Azimuthal received SEL for a towed marine vibrator; and (P) Inline received SPL for a towed marine vibrator. The colour bars at the bottom are for the SPL and SEL units, respectively. Refer also to Figure 9.

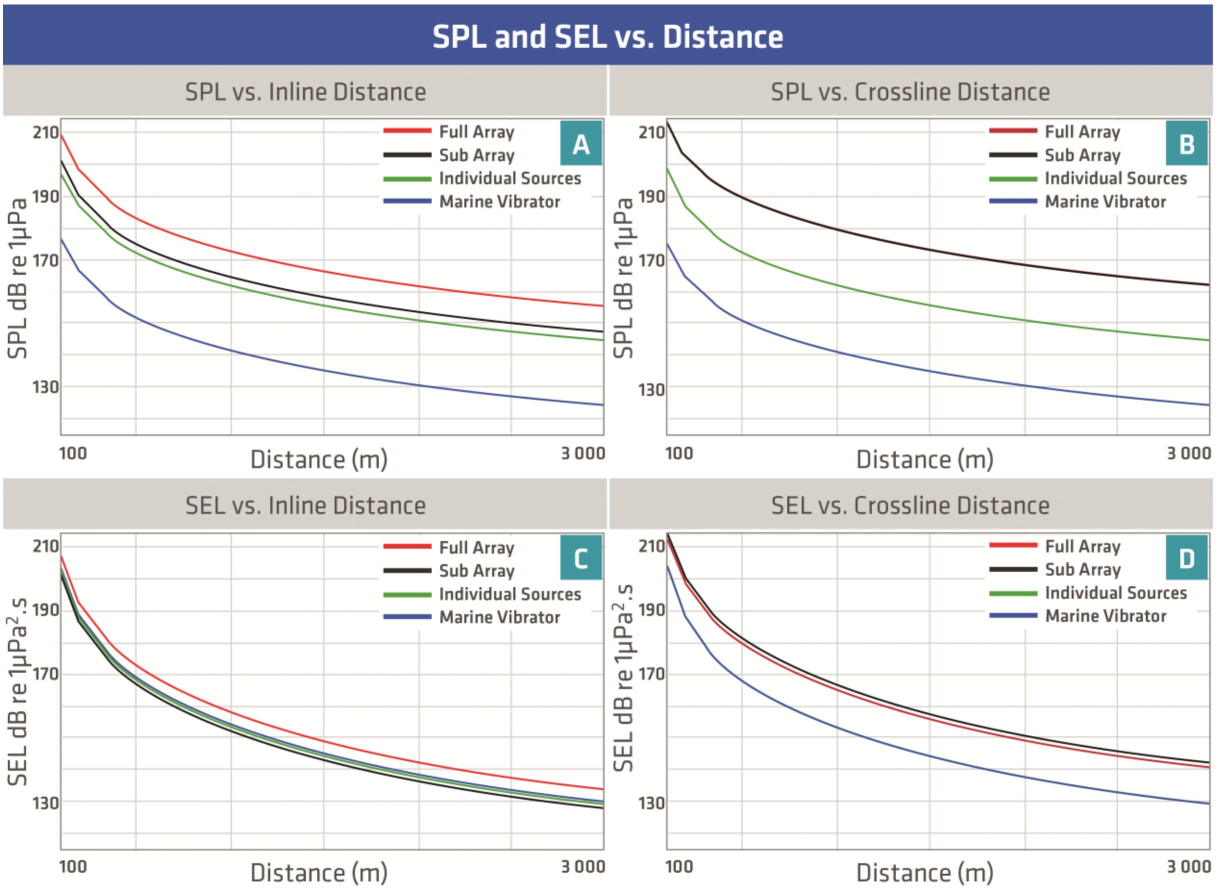

Figure 9. (A) Superimposed inline (0°) received SPL for four source scenarios in Figure 8 (array of three sub-arrays, one sub-array, an individual air gun being continuously activated, and a towed marine vibrator); (B) Superimposed crossline (90°) received SPL for the four source scenarios; (C) Superimposed inline (0°) received SEL for four source scenarios (array of three sub-arrays, one sub-array, an individual air gun being continuously activated, and a towed marine vibrator); and (D) Superimposed crossline (90°) received SEL for the four source scenarios. Each vertical line represents an increment of 500 m. 20 dB decay = 90% decay, 40 dB decay = 99% decay, and 60 dB decay = 99.9% decay.

Individual air guns obviously provide the most intriguing option to operate 'compact' sources with the lowest received sound levels, but the traditional dogma has been that such sources might be too weak and deficient in low frequency content to satisfy the requirements of seismic imaging. So I will temporarily detour into the realm of 'low frequency source concepts', before returning to some practical considerations when using individual air guns as sources.

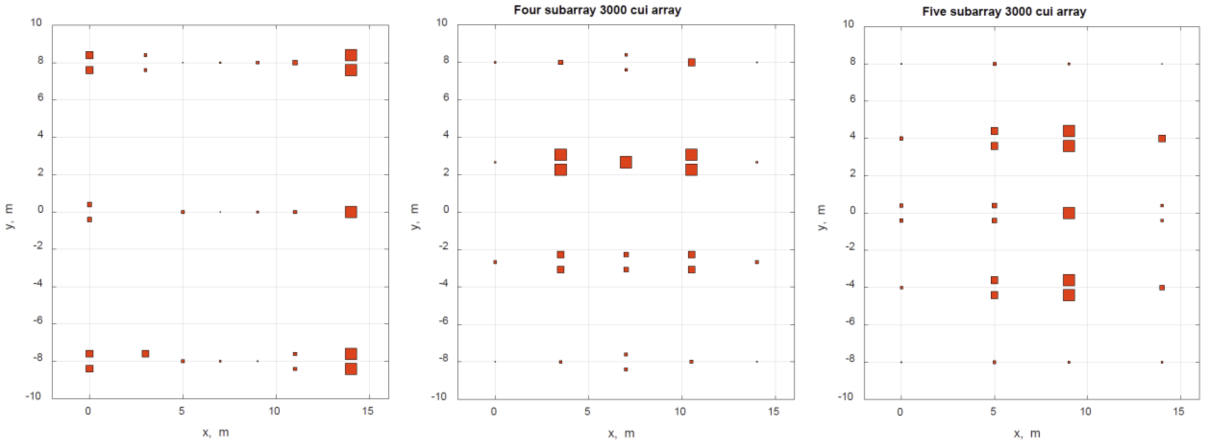

Figure 10. (left) Plan view of a typical medium-sized air gun array with total volume of 3000 cubic inches. The symbols represent the individual air guns, and their linear dimensions are proportional to those of the corresponding air gun volumes; (middle) Four sub-array rearrangement; and (right) Five sub-array rearrangement. Based upon Duncan (2017).

The Issue of Ultra-Low Frequencies

The physics of air gun operations is well understood. The low frequency content improves as air gun volume increases and/or towing depth decreases (Hegna and Parkes, 2011; Landrø and Amundsen, 2014): The free-surface 'ghost' effect favors deep-towed sources, whereas the bubble time period (increasing with decreasing source depth) favors shallower tow depths. In practice, the maximum air gun volume used is about 300 cubic inches, and the towing depth is rarely less than 5 m; both factors driven by a desire to maintain a stable emitted source wavefield. As the emitted frequency content of air gun arrays typically decays rapidly below about 7 Hz—too high for modern applications of full waveform inversion (FWI) for high resolution velocity model building or amplitude-versus-angle inversion to recover elastic impedance attributes—various initiatives have sought to fundamentally improve ultra-low frequency source output. Hopperstad et al. (2012) arranged various-sized air guns close enough in a test such that their bubble periods were tuned to that of the largest-volume air gun, but the low frequency improvement shown was marginal. Chelminski et al. (2016), Ronen and Chelminski (2017), and Watson et al. (2019) promote the concept of building an air gun with enormous volume (4000 cubic inches) and low firing pressure to increase ultra-low frequency content. A 600 cubic inch test version activated at 200-1000 psi has shown the potential to emit a source wavefield with a fundamental frequency of about 2 Hz. Recharging and cycle time would obviously be longer than for traditional air guns. Nikitin (2018) also promoted the use of very large air gun sources to facilitate 'Velocity model building surveys' (the platform for FWI), although counter-intuitively using very large source depths.

Ultra-low frequency marine vibrator concepts have also been tested in recent years. The main challenge is that the volume of water that must be displaced per cycle to maintain a specific output sound level must increase exponentially as the frequency decreases. Accordingly, Dellinger et al. (2016, 2019) and Pool et al. (2018) have described the testing of a very large MV concept operated from its own source-handling vessel in the Gulf of Mexico, and that has targeted source frequencies in the range of 2-8 Hz. More robust FWI has been the primary motivation to develop this source concept (Brenders et al., 2018), but the jury is still out on whether tangible benefits can be demonstrated, and no effort has been made yet to publish relevant benefits to elastic impedance inversion.

Figure 11 provides an interesting comparison of unmigrated (upper) and migrated (lower) stack frequency panels using the continuous source firing and recording methodology of Hegna et al. (2018) and Klüver et al. (2018). Individual air guns varying in volume between 40 and 150 cubic inches and towed at conventional depths are continuously activated several times per second, one-at-a-time, and with small, randomized firing time increments. The physics is not yet fully understood, but the observations of significant event amplitudes in the 1-2 Hz range challenge the dogma that very 'different' source concepts such as those discussed above are necessary to address the traditional lack of low frequency content in marine seismic data.

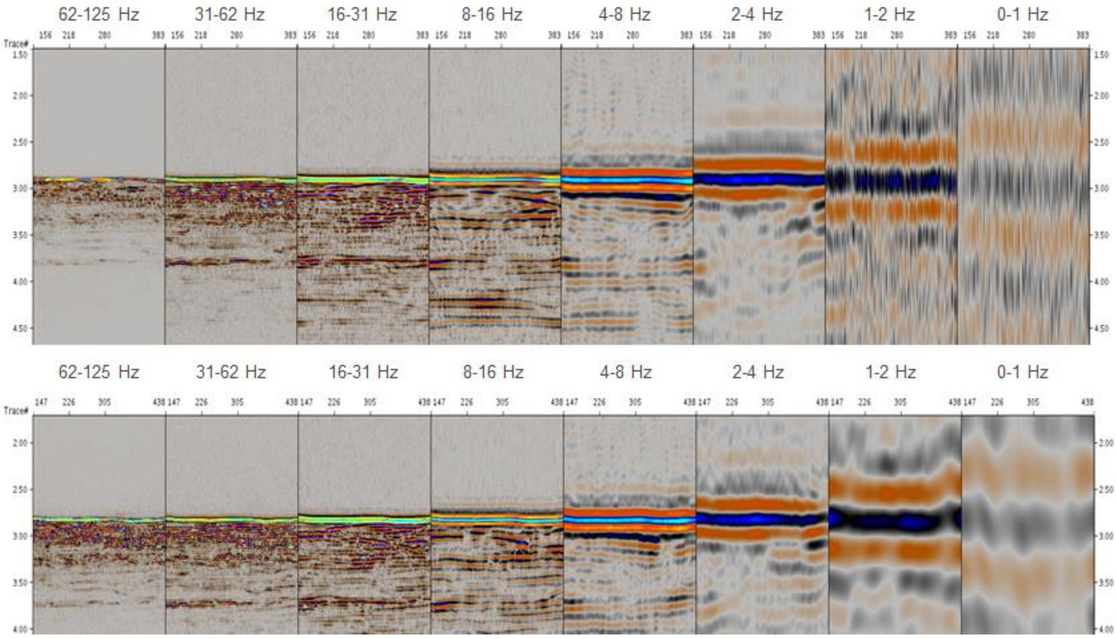

Figure 11. (upper) Unmigrated stack frequency octave panels for continuous source firing and recording or individual air guns; and (lower) Migrated stack frequency octave panels. Significant event amplitudes are observed in the 1-2 Hz range.

New Paradigms for Seismic Operations

Abma and Ross (2015) refer to 'popcorn' shooting wherein a first air gun of an array is activated at a reference location and then the remaining air guns are rapidly activated in succession to reduce the maximum pSPL applicable to the survey. Then the process repeats when the vessel has reached the next reference shot location. Each cycle of air gun activations is referenced to a traditional source interval (e.g. 18.75 m), and an inversion process reconstructs common shot gathers on a shot grid that resembles traditional acquisition with simultaneous activation of all air guns in an array. Janiszewski et al. (2017) describe the activation of air gun arrays on an irregular shot grid (with normal distribution) as the platform to exploit compressive sensing methodology: A uniform grid of shot gathers is reconstructed with a 'sparse' inversion process wherein the shot interval is equivalent to the smallest shot interval used within the irregular shot grid. Although the air gun arrays have all air guns activated simultaneously, each sail line of shot gathers is processed as a continuous dataset during the reconstruction of a uniform shot grid. The methodology of Hegna et al. (2018) and Klüver et al. (2018) shares elements of both aforementioned methods, but note that the activation of individual air guns continues without interruption along each sail line:

- Small randomized intervals between the activation of each individual air gun, with typically several activations per second
- Each sail line is recorded and processed as one continuous data volume
- Common receiver gathers are reconstructed at arbitrary (uniform) spatial intervals according to user requirements
- The accumulated energy from several air gun activations contributes to each reconstructed common receiver gather—so deep signal penetration is comparable to traditional marine acquisition—and signal-to-noise content also benefits

Figure 12 illustrates how inline spatial sampling of the source wavefield is very dense (more than once per meter), and as minimal air is needed to recharge each air gun the sub-arrays can be more flexibly deployed with large lateral spacing. Collectively, both the inline and cross-line spatial sampling of the source wavefield can be denser than any alternative method.

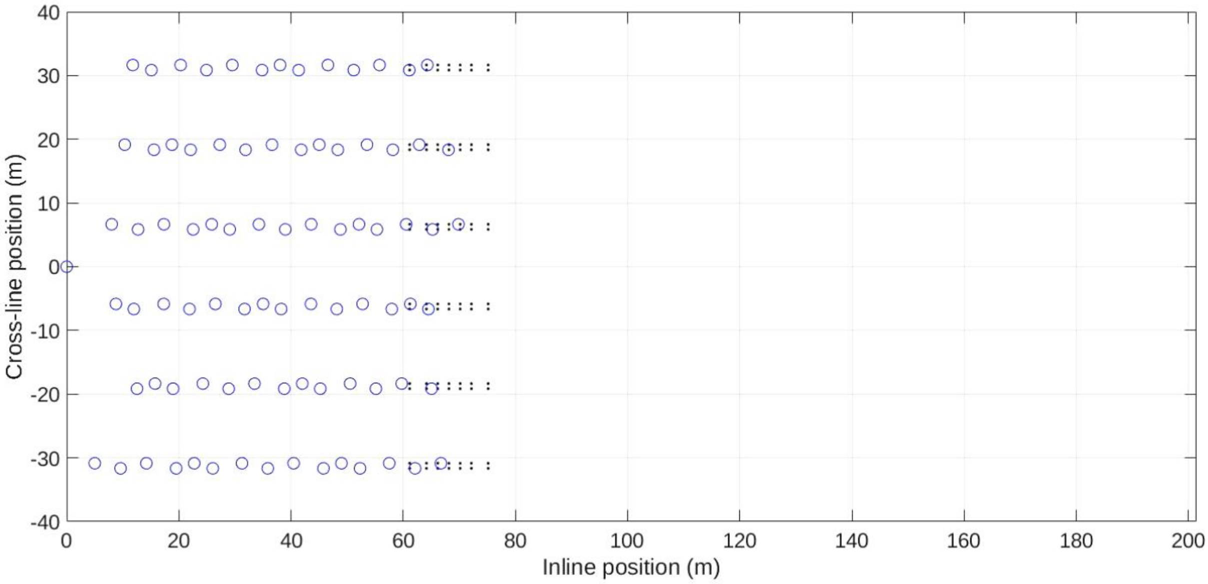

Figure 12. Schematic illustration of the spatial location of the activations of individual air guns from six sub-arrays using the methodology of Hegna et al. (2018) and Klüver et al. (2018).

Field tests in both the North Sea and Brazil (refer also to the third row of Figure 8) verify that the received pSPL is more than 20 dB (90%) less than traditional source arrays, and the received SEL—determined by the number of air gun activations per second, is 8-9 dB (almost two-thirds) less.

The 2013 Code of Conduct applicable to marine seismic surveys in New Zealand, possibly the most highly regulated country for seismic operations in the world today, categorizes three levels of marine seismic survey based upon the source type:

- Level 1: > 427 cubic inch total combined operational capability
- Level 2: 151 – 426 cubic inch combined operational capability
- Level 3: Low energy electro-mechanical sources (e.g. MVs) and < 150 cubic inch total combined operational capability (i.e. individual air guns)

Level 3 surveys are exempt from the provisions of the Code. Level 1 and 2 surveys are managed according to a comprehensive Marine Mammal Impact Assessment (MMIA), and follow a highly prescriptive set of rules, including soft-start procedures, the use of Marine Mammal Observers (MMO) and Passive Acoustic Monitoring (PAM). The implication is that acquiring a 3D marine seismic survey in continuous source mode is likely to be of lower environmental impact and far easier to manage operationally.

Summary

The use of spatially more compact marine source arrays may enable denser spatial sampling of the source wavefield and/or the receiver wavefield, may enable higher survey efficiency for appropriate survey design strategies, and may have lower environmental impact in terms of both received pSPL and SEL—with appropriate source and survey design. The air gun source strategy with the minimum environmental impact uses individual air guns activated in rapid succession.

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