Working Paper of the International Association of Geophysical Contractors
Lowest Practicable Source Levels (LPSL): The implications of adjusting seismic source array parameters

Contents

1. Executive Summary

During recent years the idea that seismic surveys could be adjusted to a "lowest practicable source levels" for a particular site or survey has garnered increasing attention with pressure from environmental organizations and regulators around the world to implement additional mitigation measures such as reducing seismic array air volumes. This is despite the fact that source volumes do not correspond linearly with source output levels (in fact, it is a cube root relationship), and that over four decades of experience demonstrates no evidence of serious injury, death or stranding of marine mammals from exposure to seismic pulses, even in the case of larger source arrays.

This paper reviews the consequences of modifying seismic source array variables (number of elements, operating pressure, air volume of the total array, air volume of the array elements, and array dimensions or geometry). This paper does not address new technologies that are not currently available for commercial application such as modified seismic source designs, baffles, screens or other new technologies. Briefly, the key parameters considered, and their impacts on sound levels generated by source arrays, include:

A. number of elements: There is a linear relationship between the number of identical elements and array loudness expressed as peak pressure (SPL_{peak})[1]; half as many identical elements would make the array half as loud, or 6 dB quieter in the direction of the downward looking beam;

B. operating pressure: There is a ¾ proportional relationship between operating air pressure and loudness expressed as SPL_{peak}; an array pressurized at 2000 psi would be about 4 to 5 decibels (dB) louder than an array pressurized at 1000 psi[2];

C. air volume: For both the individual source elements and the total array, loudness is proportional to the cube root of the ratio of different volumes, therefore a 6 dB reduction in loudness from a 240 cubic inch (cu in) element would require replacement by a 30 cu in element; and a 6 dB reduction in

[1] When comparing array output from different sizes and combinations of sources and source pressures we use the peak pressure as the metric of loudness because that is the primary output parameter of interest for the array's intended purpose. Measurements that sum the energy from multiple pressure oscillations over time such as SPL_{rms} or SEL are more appropriate for far field measurements away from the array where multi-path and other effects contribute to the received sound field.

[2] PP (primary peak) = k*P^(3/4)*V^(1/3)/P_hyd^(5/6)

loudness from an 8000 cubic inch array would require reduction of total array air volume to 1000 cubic inches;

D. array dimensions: This is the most complicated aspect of the array. While some effort will be made to explain how the geometry of the array contributes to the proper functioning of the array as a source of seismic data, the simplest statement that can be made about array geometry is that it is optimized for geophysical imaging and any changes are likely to reduce array effectiveness. A full discussion of arrays is beyond the scope of this paper.

The key take-away points are that:

1. A reduction in source air volume has a relatively minimal influence on source level; and

2. The modelled or theoretical source levels often quoted for seismic source arrays are not directly predictive of the received levels at distance in the water column because of the effect of the element separation in the array.

2. Introduction and Background

On June 18, 2013, the U.S. Bureau of Ocean Energy Management (BOEM) reached legal settlement with a group of environmental NGO's and industry intervenor-defendants in the case of *NRDC v. Jewell*, in the U.S. District Court for the Eastern District of Louisiana. The settlement set forth new seismic permit application requirements that include the following:

> The applicant must provide an estimate of the total energy output per impulse in decibels (root mean square (RMS) as described in BOEM's permit application, Section D), with respect to each energy source to be used. The applicant will verify in writing prior to conducting Deep Penetration Seismic Surveys that the proposed airgun arrays to be used are, to the extent practicable, of the lowest sound intensity level that still achieves the survey's goals. The written verification must include confirmation that the airgun array has been calibrated/tuned to maximize subsurface illumination and minimize, to the extent practicable, horizontal propagation of noise.

In addition, BOEM is obligated to convene a panel of geophysical and environmental experts "to determine whether it would be feasible to develop standards for determining […] the lowest practicable source level for a Deep Penetration Seismic Survey."

Setting aside the use of non-equivalent acoustic terminology[3], these statements have been generally interpreted to mean a goal of reducing the level of sound exposure to marine life, without losses to data quality that would jeopardize the goals of the survey and possibly lead to the need for more or lengthier surveys to compensate for lost data quality.

[3] "Sound intensity level" is not equivalent to sound pressure level averaged over some time period (RMS), nor is it equivalent to the cumulative energy within some time period (e.g. SEL). The metric of greatest interest in discussing the source array is peak pressure of the primary pulse, whereas the measures of biological interest away from the source array are typically measures of averaged pressure across the pulse (dB SPL_{rms}, usually referenced to 90 per cent of the energy in the pulse) or Sound Exposure Level (dB SEL) averaged across the multi-math propagation of a single pulse or multiple pulses.

3. A Brief Overview of Seismic Arrays

As outlined in Caldwell and Dragoset (2000) "A brief overview of seismic air gun arrays":

> The sound pressure (amplitude) generated by a seismic array is:
> 1. linearly proportional to the number of guns in the array (i.e., all else being equal, a 30-gun array will generate twice the amplitude[4] of a 15-gun array);
> 2. proportional to the firing pressure of the array (an array pressurized at 2000 psi would be about 4 to 5 decibels (dB_{peak}) louder than an array pressurized at 1000 psi; and
> 3. proportional to the cube root of the volume of the array (an 8000-in^3 array will generate about twice the amplitude of a 1000-in^3 array if they contain the same number of guns).[5]

In addition to the above source array variables mentioned by Caldwell and Dragoset (2000), the spatial dimensions of the source array also have a significant impact on the resulting source level generated by the array.

3a. *Number of elements in an array*

As noted above, the sound pressure (amplitude) is linearly proportional to the number of elements in the array. This only holds true, however, if all the elements occupy the same location, which is physically impossible. An array is typically 10 meters (m) by 15m, or more, for the purpose of enabling the timing of air bubble releases from the different elements to produce a downward beam of the lower frequencies most useful to seismic surveys (usually between 2 and 250 Hz).

Actual maximum source levels of arrays in the direction of the downward beam are generally 10-20 dB lower than the theoretical source levels predicted by the number of elements alone, and even lower in the more horizontal or lateral aspects where the additive effect from the individual elements is even less. The actual source levels will be lower because the contributions of acoustic energy from each individual element attenuate before joining the pressure pulses from other elements in the array. A significant amount of attenuation occurs over very short separation distances between elements. As the distance from the source doubles, the sound pressure level halves (think of the sound from an individual element radiating in all directions and getting thinner and thinner, like the skin of a balloon as it is inflated).

The dimensions of the source array can have more influence on the resultant output than the number of elements in the array, with output dependent on the way the elements are laid out in the source array. Increasing the number of elements in the array is done primarily to remove unwanted components such as "bubble trains" that reduce the clarity of the resulting returns from the rock layers below, as well as providing directionality. Significantly reducing the number of elements in an array will, therefore, be undesirable from the perspective of the resultant seismic data quality. *See* IAGC 2002. Further discussion of the influence the array dimensions have on array source levels can be found in section 3d.

3b. *Operating pressure of an array*

The source arrays used by the seismic industry typically operate at a pressure of approximately 2000 psi. There is very little practical opportunity of varying source levels by varying the operating pressure used. Generally, increasing the pressure requires greater compressor capacity on the seismic vessel (which is already significant) and decreasing the pressure can potentially lead to water leakage into the compression chambers, but perhaps more importantly can lead to unwanted "autofiring" when insufficient pressure in the chamber results in a premature release of air in one or more array elements and "polluting" the overall output signal with energy outside the signal of interest.

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[4] "Twice the amplitude" is equivalent to an increase of 6dB SPL re 1 µPa).

[5] The sound pressure (amplitude) is proportional to the cube root of the ratio between two volumes (Pers Comm Hughes-Caldwell 2014). Thus, 8000-in^3 will be twice the level of 1000-in^3, 800-in^3 twice 100-in^3 and 240-in^3 twice 30-in^3.

3c. *Volume of an array, including individual element volumes*

The sound pressure (peak amplitude) is proportional to the cube root of the ratio between two source volumes (Caldwell and Dragoset (2000)). Thus, an 8000-in^3 array produces only about twice the loudness of a 1000-in^3 array, all things being equal (such as the number of elements and the spatial dimensions of the array). This volume to loudness ratio holds for the sizes of single elements as well: e.g. a 240-in^3 element only generates twice the peak pressure level of a 30-in^3 element, not 8 times the level as some might assume. It is mainly the frequency components of the source signals that differ with size: larger elements produce more low frequency sound.

A single 800 in^3 element would be required to double the source output of a 100 in^3 element. However, if we were to create an array of four 100 in^3 elements we would produce twice the acoustic output in the array pressure peak compared to a single 800 in^3 element. In other words we get twice the output from only half the volume, because we have enabled the output from the four elements to be synchronized so that their peaks align. That is why we have noted that the output sound pressure level for a seismic array is more closely related to the total number of elements in the array than to the total array volume, and it is why source geometry is so important. Achieving greater peak pressure outputs from an array of smaller elements than would be achieved by a single element of the same combined volume is only possible if the pressure pulses line up, and since they cannot line up in all directions, the additive gain cannot be achieved equally in all directions.

But before we move on to the discussion of array geometry in section 3d, below, it would be good to summarize the contributions of the other three array variables, number of elements, pressurization, and air volume.

In conclusion, reducing the volume of a seismic array by removing some of the [larger] low frequency elements will have the following results:

- minimal impact on the source level of the array;
- less attenuation of the “bubble-trains” that are the source of most of the undesirable energy for geophysical imaging;
- reduction in the low frequency component of the signal (typically 2-10 Hz) will lead to non-optimized sub-surface imaging, especially in deep geological basins as often encountered in the Gulf of Mexico.

3d. *Array dimensions*

The dimensions of a source array and the number and different volume of elements it contains are very important in reducing the effect of the “bubble trains” to achieve a seismic signal that is optimum for imaging the geological objectives. Furthermore, the distance between the individual elements in the array have a significant influence on the resultant source level generated by the array, since acoustic energy is dissipated as it travels the distance needed to align with pulses from the other elements.

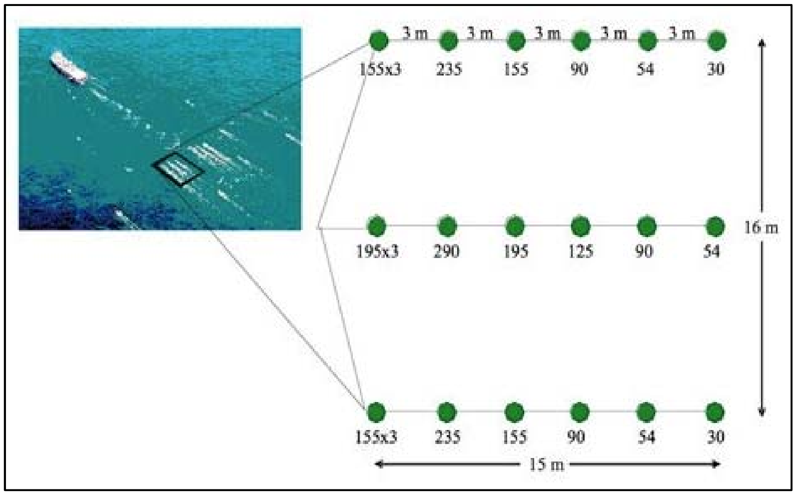

Figure 1. A typical seismic array geometry, illustrating the spacing between elements. As in this figure there are usually two such arrays towed side by side and triggered in alternation while the other array is re-pressurizing.

The alignment of the pulses from the individual elements adds to the peak amplitude of the primary pulse, but tends to create destructive interference between the subsequent pressure oscillations of the individual bubbles, reducing the number of "confusing echoes" that can interfere with the quality of the resulting geophysical images.

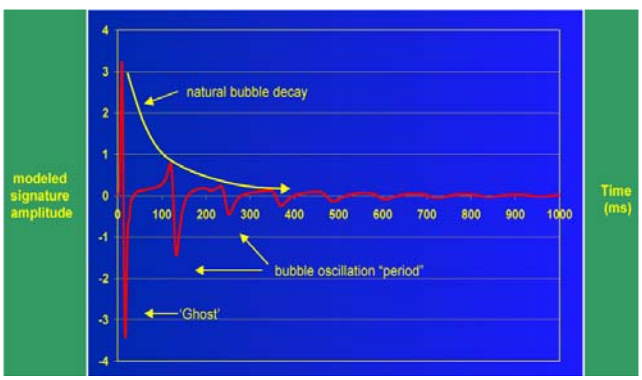

Figure 2. A plot of pressure or amplitude (vertical axis) versus time (horizontal axis) of a single source, referred to as an air-gun's pressure signature. It shows the first, or primary, positive pressure pulse due to the initial expansion of the bubble that is created by release of compressed air. The subsequent lower amplitude pulses in red are known as the "bubble train".

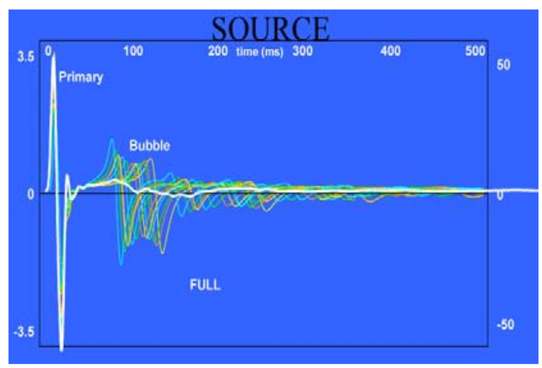

Figure 3. A series of signatures from different volume elements in an array, are summed (or coalesce) to produce the overall source signature (in white) for that array. Note that due to the different "bubble train" oscillations produced by the different volume elements in the array, the "bubble train" in the signature of the full source array is significantly minimized. In addition, as all the primary pulses of the individual elements are summed as if they had originated from the same point, the amplitude (pressure) of the composite array output is boosted compared to the individual signatures, although only in the downward direction.

(Source of Figs 2 and 3: IAGC August 2002 publication: Airgun Arrays and Marine Mammals).

Figure 4 below depicts the downward or vertical directivity of a modeled source signal in terms of azimuth, and amplitude.

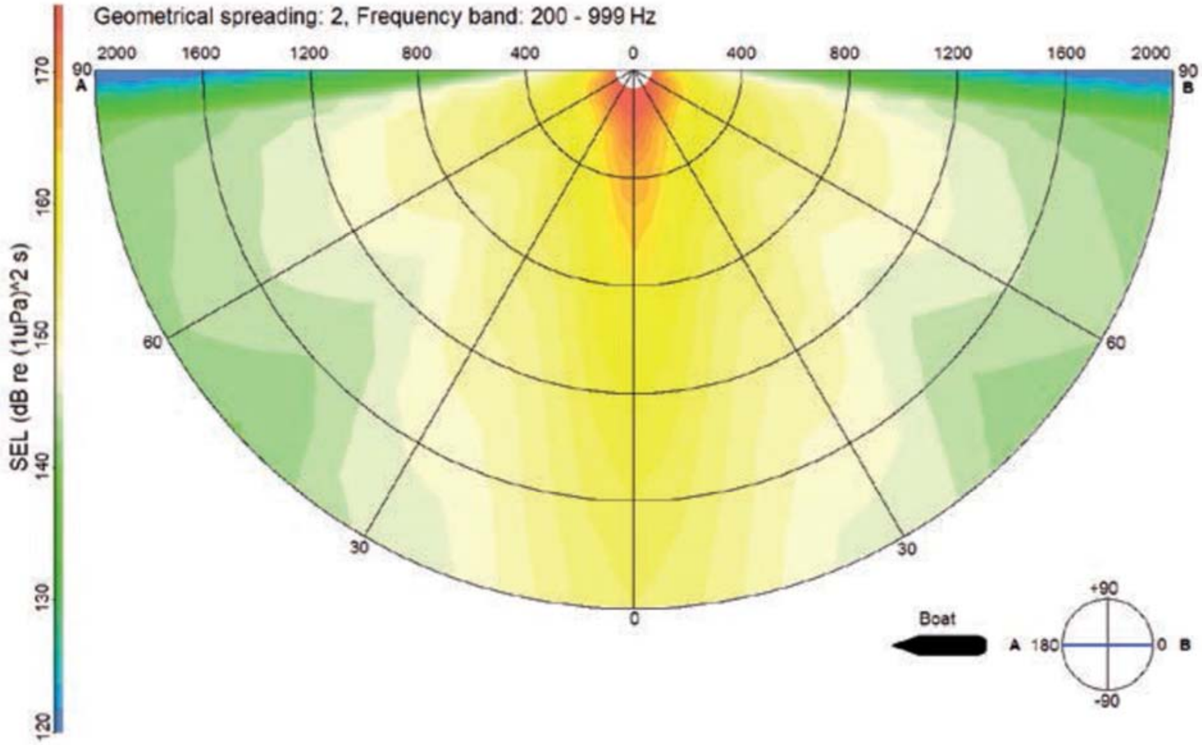

Figure 4. Polar plot of modeled 3080-in^3 source, looking downward and in cross section from port (-90) to starboard (+90), illustrating the directionality of the array output; with highest sound levels in red (170 dB) and lowest in blue (120 dB). Numbers across the top are distance from the sound source in meters. (Source: Goertz 2013).

In the horizontal or lateral direction the interaction between the elements is complex, depending on their alignment in space and time: since the elements are activated to achieve maximum coherence downward, there will be much less coherence in other directions, typically 15-30 dB less peak pressure and less suppression of bubble oscillations. Figures 5 and 6 illustrate typical irregular lateral or horizontal propagation patterns that result from element triggering patterns designed to produce a maximally coherent signal in the downward direction. Such array modeling typically exhibits the star or diamond shape seen in Figures 5 and 6, due to the rectangular shape of the array in the horizontal plane.

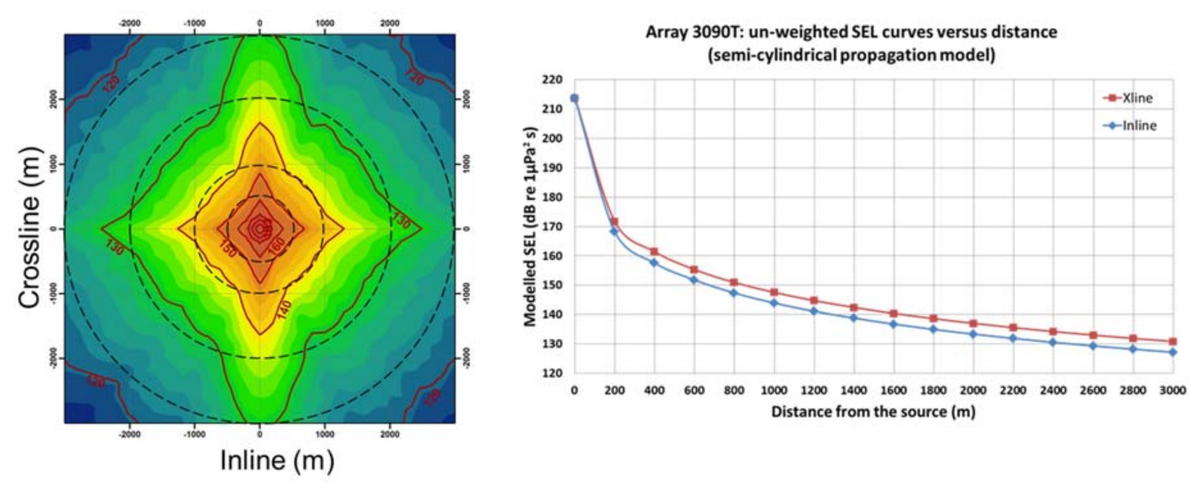

Figure 5. Modeled lateral transmission loss from a typical seismic array (Source: Goertz et al 2013, EAGE First Break).

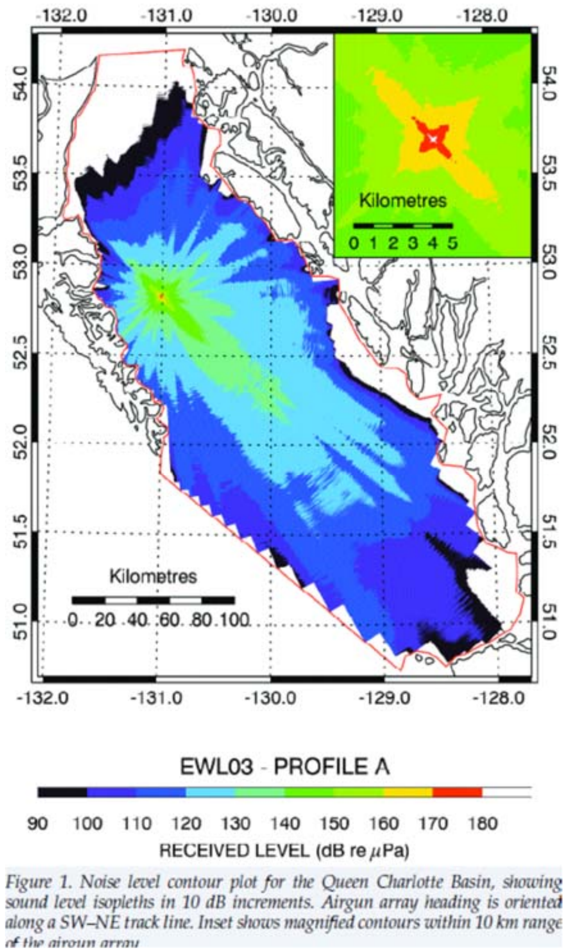

Figure 6. Modeled propagation loss for a seismic array operating in the Queen Charlotte Basin, British Columbia (from MacGillivray, 2007).

4. Examples of the Relationship between Frequency and Propagation Effects

The acoustic output of the individual elements and of the array is an impulsive waveform containing energy across a wide range of frequencies. The arrangement of elements within the array is intended to maximize and smooth the amplitude across the frequencies of greatest usefulness for seismic surveys, 2-250 Hz, but other frequencies are present within the array output and these will be differentially propagated by the environment. Two examples are provided to illustrate how the frequency composition of the array output can differentially propagate with distance.

Figure 7 below shows a comparison of two modeled sound attenuation curves from a 4130in^3 array (blue) and a 3090in^3 array (red). Because the entire complex sound output is measured at a distance, the output is presented as SEL_{90} (the energy within 90 per cent of the total signal) and not peak pressure of the primary pulse, but the two are correlated measures of the output of the two arrays. It can be seen that the output of the two arrays near the origin is nearly identical, as predicted by the cube root relationship of the array size. But over distance, the propagated energy from the two arrays diverges because the smaller array has proportionally less low frequency energy and the environment is attenuating the higher frequency component more than it is attenuating the lower frequency component of the two propagating signals. This leads to a relatively louder received level from the larger array at increasing distances. While the differential propagation can be attributed to a variety of properties of the propagating medium such as surface roughness, water depth, chemical absorption of higher frequencies (and possibly other environmental features), the difference in received levels observed at a distance is not the consequence of a simple variable like total array size, but is due to the complex interaction of the array with specific features of this particular sound propagating the environment.

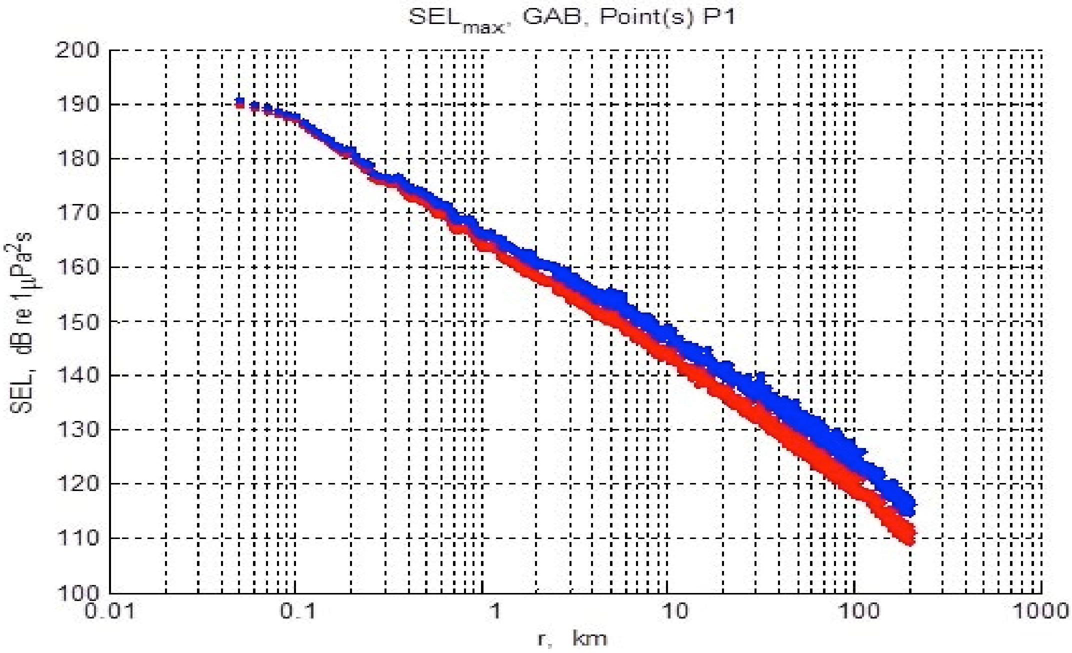

Figure 7. Modeled sound attenuation plots of 4130 in^3 (blue) and 3090 seismic arrays generated for a constant water depth of 100m in the Great Australian Bight (Source: R. McCauley, Curtin University).

Similarly, Goertz et al (2013) plotted frequency-specific sound pressure levels for a 30 cubic inch source against ambient noise levels and then modeled two frequency spectra for the 30 cubic inch source and a 3090 cubic inch array (Figure 8). Recordings of the 30 cubic inch source and associated modeled output were generated for a range of 100 meters from the source. Strong agreement between the measured and modeled 30 cubic inch source lend confidence to the modeled array output, for which there is no corresponding data.

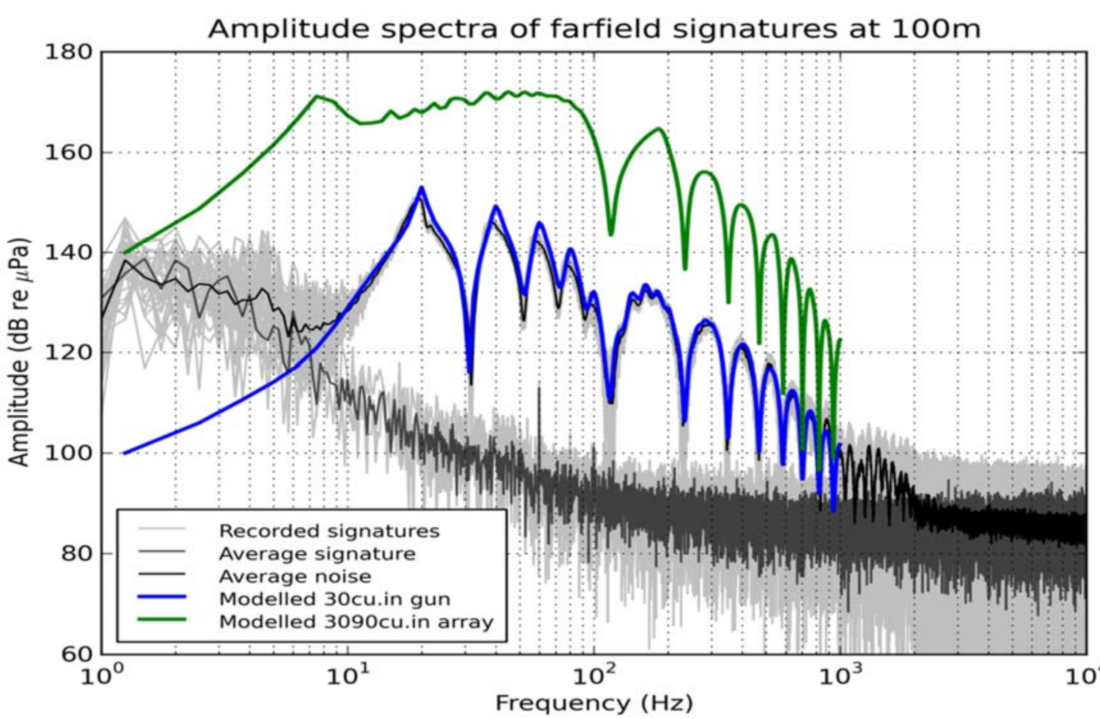

Figure 8. Modeled and measured frequency-specific amplitude for a 3090 cubic inch array (modelled) and a 30 cubic inch single source (modeled and measured). The measurements were made in a quiet fjord environment in Norway by a

data collection project sponsored by the Oil and Gas Producers Joint Industry Program (JIP). (Source: Goertz et al 2013, EAGE First Break).

Several features of the sound pressure distributed across frequencies in Figure 8 are noteworthy:

1. The summation of multiple elements of different sizes in an array increases the low frequency energy (below 100 Hz) relative to the output of a single, relatively small 30 cubic inch source,
2. The coordinated timing of multiple elements within the array greatly attenuates the amplitude fluctuations between 2 and 100 Hz, which is a critical aspect of array design for geophysical imaging clarity, and
3. Energy in frequencies above 1000 Hz in both the single small source and the modelled array is considerably lower than the energy levels at the frequencies of operational interest (2-100 Hz) and has already attenuated into the ambient noise floor for frequencies of 1-2 kHz and above at a range of only 100 meters, some 50 dB below the propagated signal levels in the frequencies of operational interest (2-100 Hz).

5. Summary and Conclusions

An examination of the aspects of a seismic array that can be adjusted demonstrates that:

1. The total volume of an array does not have a major influence on the source level of the array because the source level is proportional to the cube root of the volume;
2. The main influences on the source level of an array are not the volumes, but:
   a. The operating pressure, in which there is not much scope for variation; and
   b. The number of elements in an array.
      i. The reason for multiple elements is mainly to attenuate the bubble train that is the characteristic of single elements, and
      ii. To maximize output in the downward looking signal. Multiple elements boost the nominal source level of the primary pulse, but still fall 10-30 dB peak short of the theoretical maximum predicted by the number and size of the elements alone, due to the spatial separation of array elements.
   c. The dimensions of the array (or separation distances of the elements within the array), which is part of achieving the signal from the multiple elements as described above.

There is minimal scope for reducing the source level of an acoustic array by modifying the operating pressure or the total air volume of the array. Changing the source level by modifying the number of elements or the dimensions of the array would result in an undesirable accentuation of high frequencies and compromise the quality of seismic data with a loss of low frequencies.

A goal of achieving reductions in horizontally propagated sound will need to take into account the contributions of the environment in propagating the array output. The array is designed to optimize a relatively short down and back propagation through water and many layers of rock of varying thickness and density. Alterations of that design to achieve reduced lateral propagation will be difficult and will most certainly reduce image quality. A solution that might produce marginal decreases in laterally propagated energy, at best, in one area would likely not work under different ocean conditions, a different geology below, or different depth profiles across the track lines, to highlight only a few of the environmental variables that can affect propagation of sound through the water column.

The idea of a simple universal solution to limit or reduce array output without loss of data quality and that would yield any measureable benefit to the marine environment is impracticable and not supported by current best available scientific data.

6. Acknowledgements

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Wisløff, J. 2014. Marine Seismic Source Modelling; Estimating the output from an airgun array for a wide frequency range including near-field and directivity effects. Presentation at ESOMM 2014, Amsterdam, The Netherlands.

Additional Upcoming Reference Materials of Potential Interest:

Coste et al, 2014 – Attenuated high-frequency emission from a new design of air-gun, Abstract ACQ 4.2, 84th SEG Conference and Exhibition, Denver, Colorado, 26-31 October 2014

Haugland, T. & Sack, P., 2014 – Why are marine seismic sources so big and powerful? Abstract SS3.6, 84th SEG Conference and Exhibition, Denver, Colorado, 26-31 October 2014