Assessing the environmental impact of large-volume low-frequency marine seismic sources

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Summary

Exploration in complex geological settings, particularly beneath salt or basalt, has long recognized the need for lower frequencies. This need arises from two factors: first, the desire to extend the low-end bandwidth for FWI velocity updates, which helps mitigate the dependence of inversion results on inaccurate starting velocity models; and second, the fact that very low frequencies (<10 Hz) exhibit much better signal penetration, essential for reaching the long offsets required for resolving deep-target velocity sensitivity.

To address this need, a new generation of low-frequency pneumatic sources has been introduced to the marine seismic market. These sources share a common design principle: a significantly increased air chamber volume, which results in lower resonance frequencies of bubble oscillation. This oscillation is the primary generator of low-frequency energy in pneumatic marine seismic sources. Unlike traditional marine source arrays, these new sources operate as single devices and behave like point sources at frequencies typically observed in seismic exploration.

We will demonstrate that large-volume single sources provide the added benefit of significantly reducing high-frequency sound emissions into the underwater environment, which could be particularly important for mitigating the environmental impact of seismic activities on marine life.

Introduction

The traditional way of designing a marine seismic source is to combine several airguns of different volumes (typically between 20 to 30 individual devices) into arrays. This serves two purposes: on the one hand, summing the contributions of many guns can significantly increase the sound output, and on the other, the combination of guns with different volumes and hence different bubble resonance frequencies can suppress unwanted bubble reverberations and deliver a cleaner pulse-like signal. Typical volumes of individual gun elements range from approximately 20 to 400 cu.in., and when combined into arrays, result in total active volumes of 3,000 to 5,000 cu.in.

It has been shown by Hegna and Parkes (2011) that there is an inherent limit on the low-frequency output of such arrays, imposed by the competing interplay of bubble resonance as governed by the Rayleigh-Willis equation, and the ghost roll-off at zero frequency. Due to the Rayleigh-Willis relationship, the only way to overcome this limit with a pneumatic source is to either significantly increase the chamber pressure or the chamber volume.

The solution that has been taking hold in a new generation of low-frequency marine seismic sources currently emerging as technically and commercially viable, is a significant volume increase in combination with abandoning the traditional paradigm of building arrays for bubble diversity. Lower peak-to-bubble ratios can be dealt with much easier nowadays thanks to improved source signature deconvolution methods enabled by ghost-free broadband acquisition on the receiver side. In this paper we will discuss differences in the sound emission into the water column for such low-frequency sources in comparison to traditional marine seismic airgun arrays. We will show that, despite the much larger volume of this class of sources, their sound emission into the water is significantly lower which qualifies them also as viable solutions in areas of environmental concerns. We will focus primarily on the Gemini™ source (Brittan et al., 2020), for which partially calibrated modeling is available in Nucleus+. However, the TPS™ source (Chelminski et al.,2019) and Harmony (Rentsch and Hager, 2024) fall into the same category and will likely behave similarly once calibrated models become available. Ongoing work continues towards further improving broadband calibration for large-volume sources.

Theory

According to the Rayleigh-Willis equation (e.g., Parkes and Hatton, 1986), the bubble period T is proportional to the cube root of the volume for a single airgun:

$$T = k\frac{P^{1/3}V^{1/3}}{p_{hyd}^{5/6}}$$

where P is the chamber pressure and V is the chamber volume. The low-frequency output of an airgun is governed by the resonance frequency of the bubble oscillation (inverse of the period T). Lowering an airgun's frequency output by an order of magnitude (e.g., from 10 Hz to 1 Hz) requires increasing its volume by three orders of magnitude, assuming constant pressure. Similarly, the amplitude of a single-airgun’s signature is proportional to the cube root of the volume, expressed as $A = CV^{1/3}$ (Giles and Johnston, 1973).

However, when multiple airguns are combined into an array, the ideal array output would be the sum of all individual pulses, resulting in a proportionality that follows the integral over volume, expressed as:

$$A \sim \int V^{1/3} = \frac{3}{4} V^{4/3}$$

This is illustrated in Figure 1 which shows peak pressure of the farfield signature vs. volume for single airguns (Figure 1a) and for typical airgun arrays (Figure 1b). We note that an array of the same volume as a corresponding single gun can have up to an order of magnitude larger pressure output than the corresponding single gun. Due to airgun interactions, the use of clusters with coalescing bubbles, different airgun types and operational constraints on the array geometry, the array output does not follow exactly the above integrated proportionality, but the order of magnitude difference is about right.

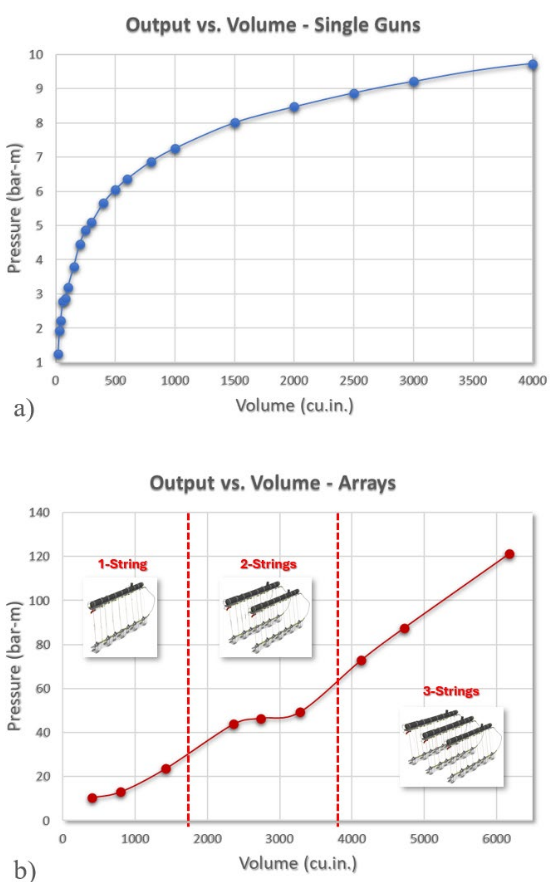

Figure 1: a) Modelled peak pressure of single-gun notional signatures vs. chamber volume. b) Modelled peak pressure for typical marine source arrays. Note the order of magnitude difference in pressure output.

While this behavior is traditionally desired to ensure sufficient energy input into the ground, the situation becomes very different when following the route of lowering the frequency output by way of volume. Not only is it unfeasible to arrange large-volume guns with several thousand cubic-inches into arrays and provide sufficient air supply, but it is also entirely unnecessary. The low-frequency energy attenuates less while traveling through the Earth, and a single-element low-frequency source provides sufficient signal for geophysical investigations.

Single-element low-frequency sources, such as Gemini, provide sufficient signal at significantly lower sound emissions while maintaining versatility for efficient acquisition at a comparable fold to conventional sources.

For example, a wide-azimuth streamer survey in Egypt with four Gemini sources and 12.5 m pop interval is described by Donaldson et al., 2024. More recently, a similar configuration has been acquired with even greater efficiency in triple-source mode.

Environmental aspects

We illustrate the difference in output pressure amplitude between Gemini and a conventional triple source array of 3,280 cu.in. in Figure 2. The peak pressure amplitude is reduced by a factor of 6, but the 2-4 Hz octave band which can be critical for sub-salt or sub-basalt exploration provides ca. 15 dB more energy. At the same time, the energy drops significantly by about 20-30 dB at high frequencies above 100 Hz, where the signal may begin to overlap with marine mammal hearing ranges.

To illustrate the difference in environmental impact between the conventional 3,280 cu.in. source and Gemini 8,000 cu.in. source, we are calculating a map of the weighted sound exposure level (SEL) around the source. Here we assume exemplary deep (1 km) water and a 20log(R) transmission loss in the water (spherical spreading). We applied the weighting function for low-frequency cetaceans after Southall, 2019.

SEL values and corresponding contour lines for TTS (temporary threshold shift) and PTS (permanent threshold shift) onsets are shown in Figure 3. We notice that the TTS contour line (168 dB re. $\mu Pa^2 s$) extends to about 450 m from the source for the 3,280 cu.in. array (Figure 3a). For the 8,000 cu.in. Gemini source, the extent of the TTS contour is much reduced to no more than 50 m from the source (Figure 3b).

Maps like this can help determine which areas around the source vessel should be monitored by protected species

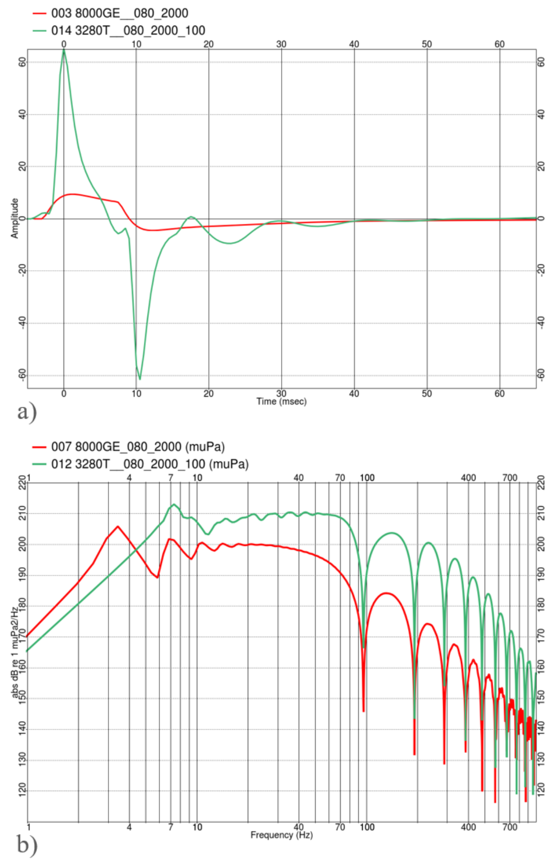

Figure 2: Modelled farfield signature for a conventional source array with a total volume of 3,280 cu.in. (green) and 8,000 cu.in. Gemini low-frequency source (red); a) Time domain - Gemini provides ~1/6th the peak amplitude (units: bar-m); b) Frequency domain - Gemini delivers ~15 dB more energy in the 2-4 Hz octave band, and 20-30 dB less energy above 100 Hz (units: dB re. 1 µPa^2/Hz at 1 m)

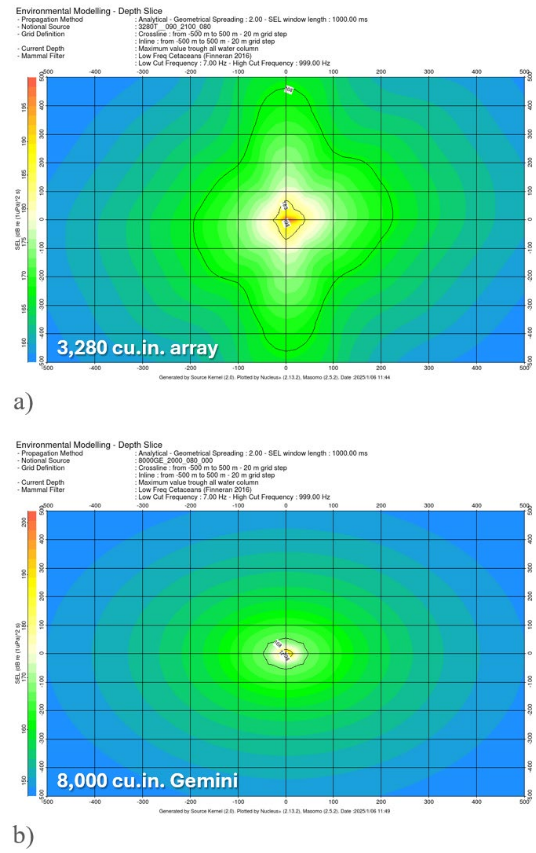

Figure 3: Maps of the low-frequency cetacean-weighted sound exposure level (SEL_{LF}) for a conventional 3,280 cu.in. array (a) and 8,000 cu.in. Gemini low-frequency source (b). Radii for the TTS threshold level (168 dB) are significantly reduced to ~1/10 for the Gemini source. Scenario assumes 1 km water depth and spherical spreading. Values represent maximum SEL over water column.

observers (PSO's), and how close an animal sighting must be for acqusition to be suspended.

Conclusions

A new generation of low-frequency pneumatic marine seismic sources enhances signal penetration in complex geology beneath salt and basalt, while simultaneously emitting significantly less energy into the water column.

This is due to two factors: first, these sources are single devices that abandon the traditional approach of signal enhancement through array formation, which subjects the output to the cube-root Rayleigh-Willis relationship. Second, the larger volume of these sources lowers the frequency range in which they are active. This results in the desired increase in low-frequency (<10Hz) energy, while also being environmentally beneficial at higher frequencies (>100 Hz), where energy emitted is significantly decreased compared to traditional seismic arrays.

Acknowledgments

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