Downloaded 03/28/15 to 50.184.92.46. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

On coherence and emitted acoustic energy of marine seismic sources

Jon-Fredrik Hopperstad, Robert Laws and David Fraser Halliday, Schlumberger Gould Research*

Summary

We address how the vertically emitted acoustic energy of marine seismic sources varies if the source elements are not synchronized. In particular, we discuss how different design alternatives to the conventional single-depth peak-tuned airgun array affect the strength of the emitted energy spectrum. For the completely incoherent case, the total vertically emitted energy of a typical 18-element array is only about 7% compared with that of a fully coherent array. This is important because firing the guns individually will result in lower SNR in the received seismic data.

Introduction

In the classical peak-tuned airgun array all guns are deployed at the same depth, and the array is synchronized so that the primary pressure peaks add constructively in the vertical farfield. The gun volumes in the conventional array are typically chosen for maximum destructive interference of the bubble oscillations, which limits the depth of the associated bubble notches in the farfield spectrum.

Avedik *et al.* (1993) suggested synchronizing the array on the first bubble peak, rather than the primary pulse, as a way of increasing the low-frequency output. Christie *et al.* (2006) compared peak- and bubble-tuning and found some improvement in output around the bubble resonance frequency, at the cost of deep bubble notches and reduced output at higher frequencies.

Smith (1984) proposed deploying subarrays at different depths and depth-synchronizing the firing such that primary peaks align in phase. For this multi-depth source the coherence of the vertical downgoing wavefield is similar to the classical peak-tuned single-depth array, while the coherence of the ghost reflection is reduced by the staggered firing. This design idea has since been adopted by several authors.

Multi-depth sources allow greater flexibility in shaping the source spectrum and to partially fill high-frequency ghost notches. However, for a synchronized array, several studies have found that the output below the bubble resonance frequency is practically unaffected by the source depth (Christie *et al.*, 2006; Hegna and Parkes, 2011). Indeed, Hopperstad *et al.* (2012a) found an even stronger limitation: the output well below the lowest bubble resonance frequency is determined by the total quantity of air released, not how the air is distributed between guns in the array, nor how many guns are used, nor at what depths they are deployed (provided they are depth-synchronized), nor at what pressure the airguns are fired. At these low frequencies the output appeared to be determined by the product of the firing pressure and the total source volume for all the array designs considered.

This interesting observation can be better understood when considering the coherence of the individual source element spectra. Detuning the array has been suggested by several authors for different purposes: Hopperstad *et al.* (2012b) proposed mild detuning for environmental purposes, Parkes and Hegna (2011) proposed moderate detuning with time- and depth-distributed guns for source-side deghosting, Robertsson *et al.* (2012) discussed orthogonal shot sequences for source gradient computation, and Abma and Ross (2013) proposed a similar concept using 'popcorn' firing for simultaneous source separation. The emitted acoustic energy for these different classes of source synchronization depends on the coherence of the array. In this abstract we reduce the coherence of the array by gradually relaxing the array synchronization. We discuss the effect of the reduced array coherence on the emitted acoustic energy in different bandwidths. We consider especially the energy that is emitted in the vertical direction, i.e., where conventional source designs aim to maximize the output.

The farfield source spectrum

The farfield spectrum of a general multi-depth source array is given by

$$W(\mathbf{k},\omega)=\sum_{n=1}^{N}\left[\begin{matrix}S_n(\omega)\cdot\exp\left(jk_x x_n+jk_y y_n\right)\\ \cdot G(k_z,z_n)\cdot\exp(-j\omega\tau_n)\end{matrix}\right] \qquad (1)$$

where ghost response $G(k_z, z)$ is

$$G(k_z,z)=\exp(jk_z z)+\rho\exp(-jk_z z) \qquad (2)$$

where $S_n(\omega)$ are the monopole spectra, x_n, y_n, z_n are the coordinates of the N source elements, k_x, k_y, k_z are the respective spatial wavenumbers, ρ is the sea-surface reflection coefficient, ω is the angular frequency, and τ_n are the time-shifts that control the coherency of the array; e.g., setting $\tau_n = (z_n - z_{\min})/c + \zeta_n$, where c is the acoustic velocity, aligns the vertically downgoing wavefield subject to a random time delay ζ_n.

The total acoustic energy emitted in the vertical direction is given by

$$E_{\text{vert}}=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|W(k_z,\omega\,|\,k_{x,y}=0)\right|^2 d\omega \qquad (3)$$

which for the incoherent case can be simplified to

© 2014 SEG
DOI http://dx.doi.org/10.1190/segam2014-1311.1

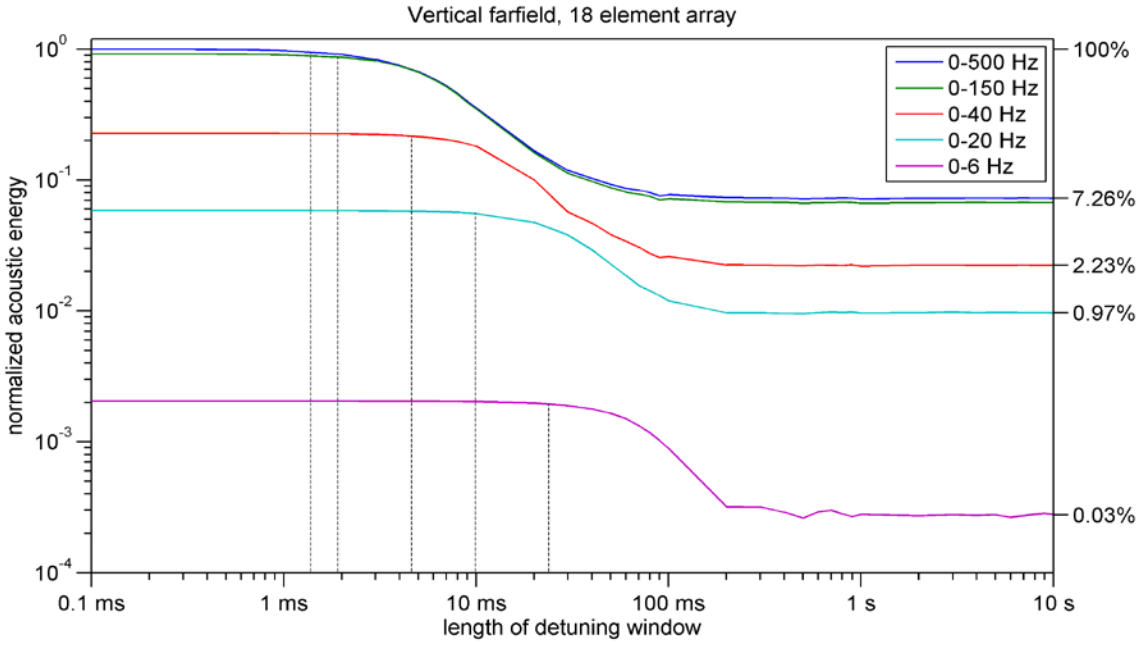


Figure 1: Mean acoustic energy (averaged over 300 realizations per window length) of a conventional peak-tuned single-depth airgun array as a function of the length of the desynchronization window. For each realization the firing time of each gun in the array is perturbed; the random firing delay is drawn from a uniform distribution of the specified window length. The farfield signature computation is done using nearfield measurements of single guns and clusters. Acoustic interaction between the bubbles is ignored. The vertical lines indicate the window length associated with the 95% output level of each case.

$$E_{\text{vert}}^{\text{incoherent}} = \frac{1}{2\pi}\sum_{n=1}^{N}\int_{-\infty}^{\infty}\left|S_n(\omega)\cdot G(k_z, z_n)\right|^2 d\omega \qquad (4)$$

This lower bound represents the case where the individual source spectra are totally incoherent. In this case the total acoustic energy is given by the sum of power spectra of the guns fired individually; in contrast to the fully coherent case where the acoustic energy is given by the power spectrum of the sum. It is important to note that since the emitted energy is proportional to the magnitude-squared, the principle of superposition does not apply to the emitted energy; it only applies to the wavefields (Laws *et al.*, 1988 and 1990). Consequently, for the special case of identical source elements, the total acoustic energy for the fully coherent case is a factor *N* higher than for fully incoherent array spectra.

Gradually detuning the source array

We first consider a conventional peak-tuned 5100 in^3 airgun source array comprising 18 elements; all deployed at 5 metres depth and arranged in three identical subarrays. The case of perfectly aligned primary peaks will be used as reference. We apply a random time delay to each gun and calculate the emitted energy in the vertical direction for each realization. Figure 1 shows the result of this exercise with detuning delays ranging from 1 ms to 10 s. The curves were normalized by the emitted acoustic energy in the 0-500 Hz bandwidth for the case with perfect primary peak alignment.

The figure shows that delays less than 1 ms have hardly any effect on the energy over the seismic bandwidth. The 0-500 Hz energy drops to 50% when the maximum delay is greater than about 7.5 ms, and the array appears fully incoherent for delays greater than 200 ms. The acoustic energy for the incoherent case is only 7.3% of that of perfect primary peak alignment; this value is close to 1/18≈0.056 (the expected value if we had chosen to use 18 identical elements).

The different coloured curves show the emitted acoustic energy for various bandwidths, and the vertical lines denote window length associated with their 95% output level. For example the 0-40 Hz (red) curve shows that the emitted energy is 23% when the primary peaks are perfectly aligned (relative to the 0-500 Hz case); firing delays less than 5 ms have hardly any effect on the acoustic energy in the 0-40 Hz bandwidth. Note the array appears more robust to detuning the lower the bandwidth considered, as might be expected.

Downloaded 03/28/15 to 50.184.92.46. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

© 2014 SEG

DOI http://dx.doi.org/10.1190/segam2014-1311.1

Downloaded 03/28/15 to 50.184.92.46. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

The 0-6 Hz case is of particular interest, as this is the emitted energy below the bubble resonance frequency. As discussed earlier, Hopperstad *et al.* (2012a) found that the output in this band was entirely determined by the product of the firing pressure and the total source volume for conventionally synchronized arrays. However, Figure 1 shows that the very-low-frequency output is affected for detuning delays greater than 20 ms, and that the emitted energy is halved when the detuning window is about 90 ms; furthermore the individual element spectra are effectively incoherent for delays greater than 200 ms.

Coherence of non-conventional array designs

Next we consider alternatives to the conventional single-depth array. Figure 2 compares the power spectra of array designs with different synchronization strategies. The spectra have been averaged over 1/10 octave bands to visually reduce the notches so that the overall output levels can be compared. Figure 3 shows the cumulative total acoustic energy of the same spectra without smoothing.

We first discuss peak-tuning (blue) vs. bubble-tuning (red); both with all guns at 5 m depth. Aligning the first bubble peaks, rather than the primary pulses, does result in slightly more output in the region of the bubble resonance frequency, i.e., around 7-15 Hz. However, aligning the bubble peaks results in the primary peaks being misaligned by up to 70 ms (not shown); this results in significant notches in the bubble-tuned spectrum above ~28 Hz. Furthermore, because of the reduced coherency of the primary peaks, the cumulative acoustic energy is lower than that of the peak-tuned array at frequencies above 25 Hz, and the total acoustic energy is only 27% in the full 0-500 Hz bandwidth.

With multi-depth sources one cannot maintain the coherence of both the down- and upgoing wavefields. Depth-synchronization aligns the downgoing wavefield, while the ghost reflections are spread in time; thereby reducing the coherence of the ghost. Here we consider the case where the middle subarray is deployed at 7.5 m, while the outer subarrays are kept at 5 m; the same as the single depth reference. The solid green curve in Figure 2 and Figure 3 shows the case of the depth-synchronized V-source. Note that the total acoustic energy in the full 0-500 Hz bandwidth is 90%. The reduction in emitted energy is due to the misalignment of the ghost reflection from the centre subarray relative to the ghost of the outer strings.

Next we consider the case of mild detuning that substantially retains the output in most of the seismic frequency band. The dashed green curves show two such examples. Here the guns are depth-synchronized, but with an additional random firing delay applied to each gun; in this case limited to 3 ms and 10 ms. The length of the detuning window controls the spectral coherency, as previously observed in Figure 1.

The cyan curve shows an example of a time- and depth-distributed source. Here the firing of the two depth layers is shifted by 100 ms. Pseudo-randomly varying the firing of the depth layers may facilitate separating the up- and downgoing wavefield. However, the time shift creates several deep notches in the emitted power spectrum, and the total acoustic energy is significantly reduced, i.e., 59% of the total acoustic energy of the conventional peak-tuned reference.

Finally we consider the case of totally incoherent wavefields. The black curve shows the effect of 'popcorn' firing (Abma and Ross, 2013), wherein all guns have been pseudo-randomly fired within a 10 s shot cycle. In practice the detuning window could have been constrained to about 200 ms with substantially the same result. The loss in array coherence results in significantly lower output over the entire seismic bandwidth; the total vertically emitted acoustic energy is only about 7% of the conventional reference. Furthermore, the spectrum exhibits deep notches which here have been masked by the 1/10 octave smoothing (applied to facilitate visual comparison).

Discussion and conclusions

The total vertically emitted source energy is given by the integral of the squared magnitude spectrum of the vertical farfield signature. Array designs that result in coherent wavefields emit significantly more acoustic energy than when the source elements are fired independently. For the completely incoherent case, the total emitted energy is only about $1/N$, across the whole seismic bandwidth, compared with that of a fully coherent array; i.e., about 7% for a typical 18-element array.

The conventional single-depth peak-tuned array emits the most source energy, over the full seismic frequency band, of the various classes of array designs considered. This is because both the primary wavefields and the ghost reflections are synchronized. Controlling the range of firing delays allow array designers to retain the coherency at lower frequencies, while reducing the (incoherent) output at higher frequencies.

In this abstract we have discussed how the coherency of primary wavefields and the ghost spectra affect the total vertically emitted acoustic energy of the source. We have not considered how subsequent data processing might mitigate the loss of emitted source energy from array designs with reduced coherence. However, it is clear that a significant reduction in emitted energy will pose an SNR-challenge for subsequent data-dependent processing.

© 2014 SEG

DOI http://dx.doi.org/10.1190/segam2014-1311.1

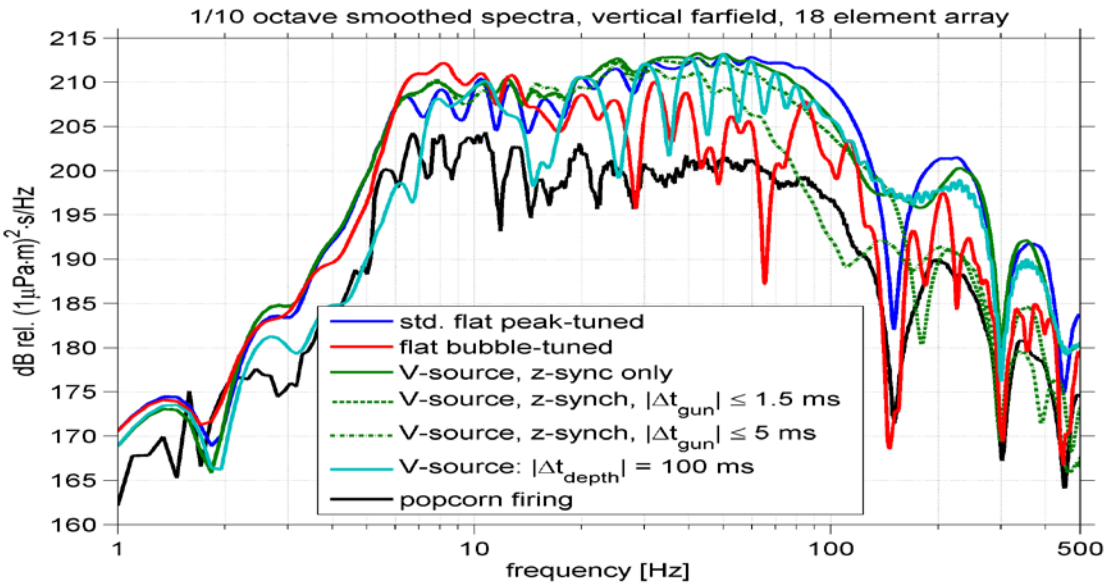


Figure 2: Power spectra of a 3-string airgun array with a total volume of 5100 in^3 for which different synchronization strategies and depth deployments are used. The spectra have been averaged over 1/10 octave bands. Blue curve: conventional peak-tuned array at 5 m depth. Red curve: all guns at 5 m depth and the array synchronized on the first bubble peak. Green solid curve: the subarrays deployed in a V-configuration at 5 and 7.5 m depth and synchronized to align the vertical downwards propagating wavefield. Green dashed curves: the same V-source with additional detuning delays of ±1.5 ms and ±5 ms. Cyan curve: the same V-source where firing of the deep strings is delayed by 100 ms. Black curve: all guns at 5 m depth and fired at a random time within a 10 s time window (popcorn firing).

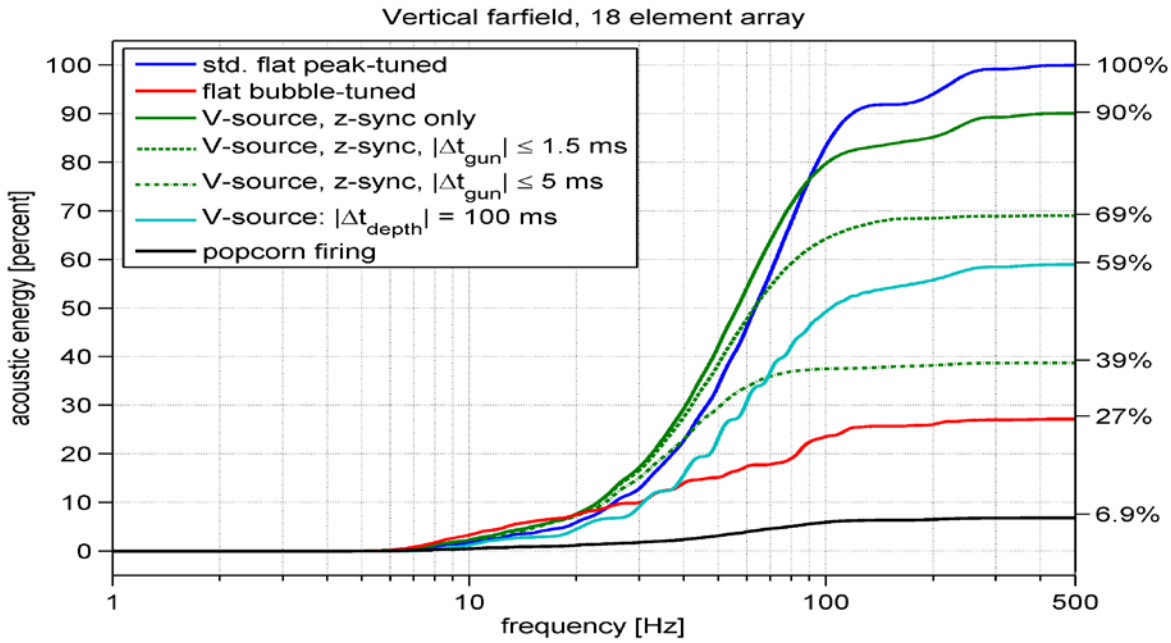


Figure 3: The cumulative acoustic energy of the power spectra in Figure 3 (without the 1/10 octave smoothing applied).

Downloaded 03/28/15 to 50.184.92.46. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

© 2014 SEG

DOI http://dx.doi.org/10.1190/segam2014-1311.1

http://dx.doi.org/10.1190/segam2014-1311.1

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2014 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Abma, R., and A. Ross, 2013, Popcorn shooting: Sparse inversion and the distribution of air-gun array energy over time: 83rd Annual International Meeting, SEG, Expanded Abstracts, doi: 10.1190/segam2013-0592.1.

Avedik, F., V. Renard, J. P. Allenou, and B. Morvan, 1993, Single bubble air-gun array for deep exploration: Geophysics, **58**, 366–382, http://dx.doi.org/10.1190/1.1443420.

Christie, P. A. F., Z. C. Lunnon, R. S. White, and N. Kusznir, A., Roberts, A.W. Roberts, C. Parkin, L. Smith, J. Eccles, D. Healy, N. Hurst, V. Tymms, A. Chappell, and R. Fletcher, 2006, iSIMM experience with peak- and bubble-tuned sources for generating low frequencies: 68th Annual InternationalConference and Exhibition, EAGE, Extended Abstracts, A034.

Hegna, S., and G. Parkes, 2011, The low-frequency output of marine air-gun arrays: 81st Annual International Meeting, SEG, Expanded Abstracts, 77–81.

Hopperstad, J.-F., R. Laws, and E. Kragh, 2012a, Hypercluster of air-guns — More low frequencies for the same quantity of air: 74th Annual International Conference and Exhibition, EAGE, Extended Abstracts, Z011.

Hopperstad, J.-F., R. Laws, and A. S. Melbø, 2012b, Method for optimizing acoustic source array performance: U. S. Patent 8,174,927.

Laws, R., G. Parkes, and L. Hatton, 1988, Energy interaction: The long-range interaction of seismic sources: Geophysical Prospecting, **36**, no. 4, 333–348, http://dx.doi.org/10.1111/j.1365-2478.1988.tb02167.x.

Laws, R., G. Parkes, and L. Hatton, 1990, Erratum: Energy interaction: The long-range interaction of seismic sources: Geophysical Prospecting, **38**, no. 1, 104, http://dx.doi.org/10.1111/j.1365-2478.1990.tb01838.x.

Parkes, G., and S. Hegna, 2011, An acquisition system that extracts the earth response from seismic data: First Break, **29**, no. 12, 81–87.

Robertsson, J. O. A., D. Halliday, D.-J. van Manen, I. Vasconcelos, R. Laws, K. Özdemir, and H. Grønaas, 2012, Full-wavefield, towed-marine seismic acquisition and applications: 74th Annual International Conference and Exhibition, EAGE, Extended Abstracts, Z015.

Smith, G. C., 1984, Three-dimensional air gun arrays: 54th Annual International Meeting, SEG, Expanded Abstracts, 282–285.

Downloaded 03/28/15 to 50.184.92.46. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/