Introduction to air guns and air-gun arrays

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The effect of seismic operations on marine mammals has been debated vigorously for years. Some feel that these operations could harm the animals. Others, based on anecdotal evidence of marine mammals swimming (or even playing) near active air-gun arrays, feel that harmful effects are unlikely. They claim that such evidence indicates, at the very least, that air guns do not physically damage the animals. Still others have relied on acoustic measurements to argue that any potential effect on the marine mammal population within a seismic survey area is negligible. Because of the importance of the discussion, the seismic industry has conducted numerous tests and monitoring studies to try to address this issue. To date, those studies have not identified any harmful long-term effects due to the proximity of marine mammals to air guns. Why then, does the debate continue?

The answer may lie in the shear complexity of the issues. Air-gun design, underwater acoustics, animal behavior, and marine mammal physiology are complex subjects and interactions between them are even more complicated. Although many debate participants are experts in one or more of these fields, none is an expert in all. Thus, individuals can interpret the same data in different ways and report their interpretations using different terms. Suppose two individuals with varying backgrounds observed a dolphin jumping near an active air-gun array. One might see a dolphin "leaping from the water to avoid the noise" while the other may conclude that same dolphin is "playing in the air bubbles."

Because of this communication problem and a lack of definitive scientific studies, no clear consensus has been reached about how air guns affect marine mammals. Thus, many organizations have recommended mitigation practices until a clear answer is found. One common mitigation procedure is air-gun ramp-up, in which guns in an array are turned on individually over several minutes. Presumably, any animal that finds the sound annoying will leave before the sound becomes loud enough to do any harm. Another mitigation measure is to employ trained observers to watch for marine mammals near a seismic source and turn the source off if they come within a certain range of the guns (based on sound pressure levels). These measures have been adopted by several countries, but there is little evidence that they are effective. There is, however, a great deal of evidence that they are costly to the seismic industry. How then should we identify potentially harmful long-term effects of air-gun arrays on marine mammals and design appropriate, sensible mitigation procedures if such effects are found?

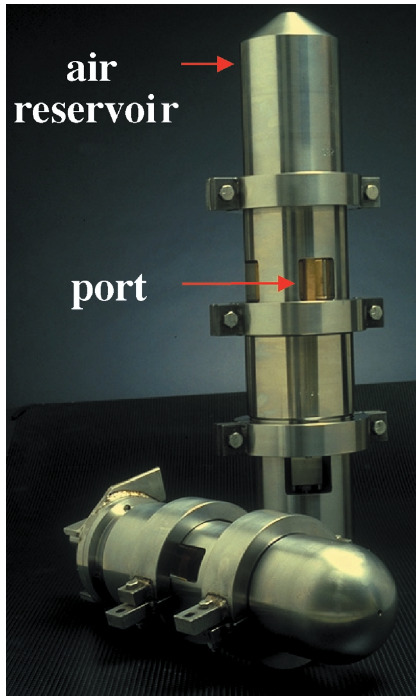

Figure 1. Two typical internal-shuttle air guns.

The answer is improved communication and cooperation among all concerned. Many scientific studies are being planned to learn more about the effects of sound on marine mammals, particularly on their hearing, and about the effectiveness of mitigation procedures. If those studies are to provide useful data, the seismic industry, government agencies, environmental scientists, and marine biologists need to share their expertise. Thus, this short article is offered in a cooperative spirit to those not intimately familiar with air guns and how the seismic industry uses them.

Air guns and air-gun arrays. A typical air gun is a relatively simple mechanical device that stores compressed air in a reservoir and releases it rapidly through small ports when a firing command is received. The ports are opened and closed by either an external movable piece called a sleeve or an internal movable piece called a shuttle (Figure 1). When an air gun fires, part of the energy contained in the escaping compressed air is converted to sound, thereby generating a seismic signal that travels into the earth's subsurface. Air guns are about 4-8 inches in diameter. Air reservoirs range from 10 to 500 in^3. The operat-

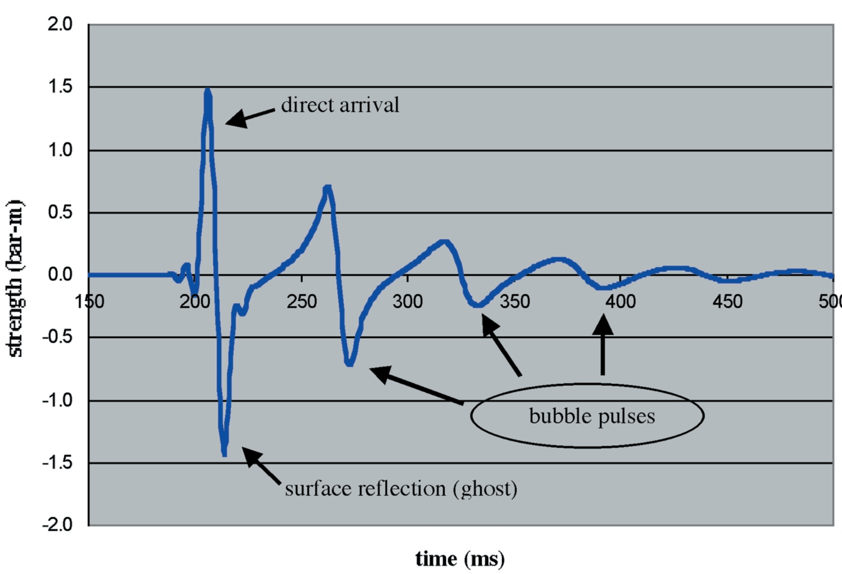

Figure 2. Signature of a single 40-in^3 air gun as recorded by a hydrophone 300 m below the gun.

ing air pressure is usually around 2000 psi, and guns are generally deployed 3-10 m below the water surface.

The characteristic sound produced when an air gun fires underwater is called its pressure signature (Figure 2). The signature has three main components: (1) the so-called direct arrival, the sound produced when the air gun's ports first open; (2) the source ghost, the reflection of the direct arrival from the water surface and which has opposite polarity from that of the direct arrival because the reflection coefficient of the water-air boundary is negative; and (3) the bubble pulses produced by the expansion-collapse cycle of the air bubble created in the water when an air gun fires. Note that each bubble pulse contains sound coming directly from the bubble, followed by the sound from the bubble that reflects from the water surface.

The important properties of an air-gun's signature are characterized by two parameters, strength and bubble period. Strength is simply the amplitude of the sound, measured in pressure units at the direct arrival's peak (peak strength) or from the direct arrival's peak to the ghost arrival's peak (peak-to-trough strength). The bubble period is the time between consecutive bubble pulses. The signature in Figure 2 has peak strength of 1.5 bar-m (these units are explained below) and a 57-ms bubble period. The strength and bubble period of an air gun depend on size, depth in the water, and initial firing pressure. Table 1 summarizes the relationships between these five quantities.

For a couple of reasons, the sound from a single air gun is generally not an acceptable seismic source. First, the signature of a single gun is too weak to produce a good signal-to-noise ratio at depth. Secondly, because of bubble pulses, the signature of a single air gun is far from being an ideal impulsive seismic wavelet. Data shot with a single gun face difficult deconvolution processing to remove bubble pulse reverberations. Both problems can be overcome using the tuned air-gun array concept, in which many guns of different, carefully selected volumes are fired simultaneously. As shown in Figure 3, direct arrivals from individual guns sum coherently below the array, thereby producing a sound much louder than that from a single gun. On the other hand, sounds from bubble pulses add up incoherently, thereby attenuating them relative to the direct arrival. The amount of such tuning is described by the primary-to-bubble ratio (PBR), which is the peak-to-trough strength of the direct arrival divided by the peak-to-trough strength of residual bubble pulses. The tuned-array signature at the bottom of Figure 3 is much closer to the ideal seismic wavelet, a perfect impulse, than signatures from the individual guns.

Table 1. Dependence of an air-gun signature on gun parameters

	Strength (S)	Bubble period (T)
Gun volume (V)	$S \propto V^{1/3}$	$T \propto V^{1/3}$
Firing pressure (P)	$S \propto P$	$T \propto P^{1/3}$
Gun depth (D in m)	complicated	$T \propto (10 + D)^{-5/6}$

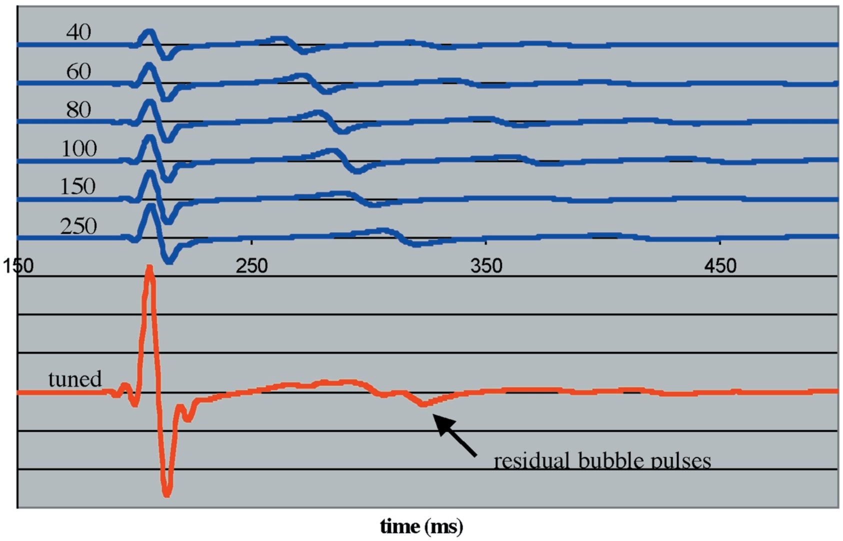

Figure 3. Concept of tuned air-gun array. Blue signatures come from individual guns whose volumes, in cubic inches, are on the left. If those six guns are placed in an array and fired simultaneously, they produce the red signature at a hydrophone 300 m below the array. The array's PBR is 8.6.

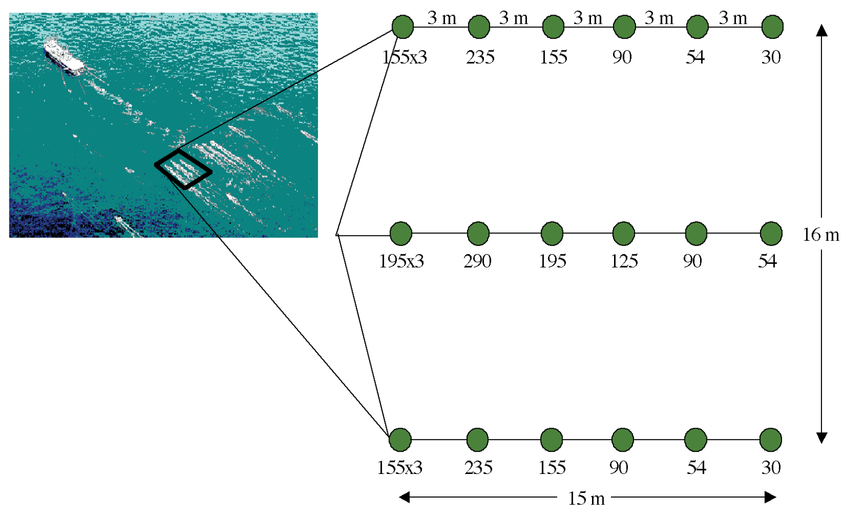

Figure 4. Plan view of typical air-gun array. Numbers below the gun stations (green circles) are gun volumes (in^3). The 155 × 3 notation indicates three guns, each with a volume of 155 in^3, so close together that their air bubbles coalesce after the guns fire. Such so-called "cluster guns" produce sound more efficiently than a single large gun. (Figure courtesy of Schlumberger).

As shown in Table 1, peak sound pressure by an air gun is proportional to the cube root of the volume of compressed air stored in the gun. This simple relationship means that the most efficient way to create sound using a fixed compressed air capacity is to partition that air among an array of many small air guns rather than an array of a few large guns. For example, two 50-in^3 air guns fired together are almost 60% more efficient than a single 100-in^3 gun ($2\ (50^{1/3}\ /\ 100^{1/3}) = 1.59$). To make use of this efficiency, a typical

Table 2. Configuration of modeled air-gun array

String #	Element #	Volume (in^3)	In-line coordinate (m)	Cross-line coordinate (m)
1	1	150 + 150	0.0	-10.0
1	2	90 + 70	4.3	-10.0
1	3	115	7.7	-10.0
1	4	80	10.4	-10.0
1	5	55	12.9	-10.0
1	6	40	15.0	-10.0
2	1	150 + 150	0.0	0.0
2	2	90 + 70	4.3	0.0
2	3	115	7.7	0.0
2	4	80	10.4	0.0
2	5	55	12.9	0.0
2	6	40	15.0	0.0
3	1	150 + 150	0.0	10.0
3	2	90 + 70	4.3	10.0
3	3	115	7.7	10.0
3	4	80	10.4	10.0
3	5	55	12.9	10.0
3	6	40	15.0	10.0

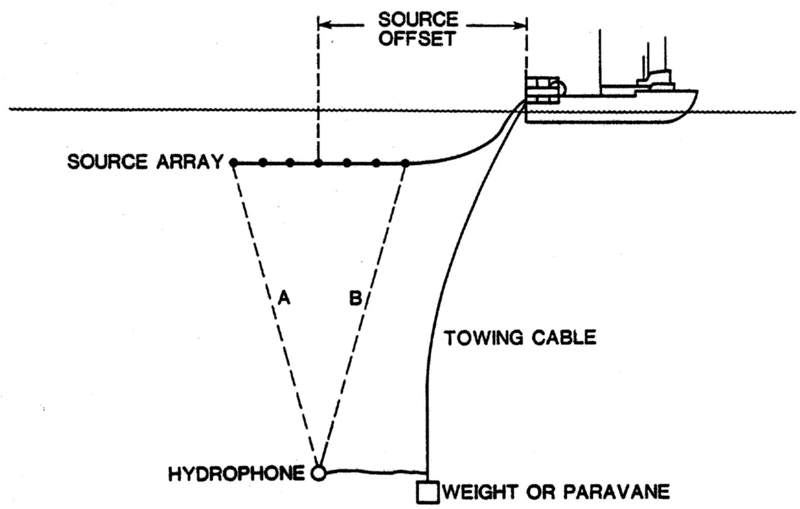

Figure 5. Equipment configuration for a far-field signature measurement. For a typical array, distance A = 300 m.

marine seismic source has a large number of small guns rather than a few larger guns. Some air-gun arrays have as many as 100 guns, but 25-50 is more usual. A typical array is shown in Figure 4.

Signature measurements. A disadvantage of having an array-like seismic source is that measuring the output is difficult. Sound pressure created at some distance by a single air gun is inversely proportional to that distance. Therefore, a detector at any distance from the gun can measure its pressure output, provided that the measured quantity is corrected for the distance that the sound travels. For an array, however, detector placement is crucial—a position must be found where the detector is equidistant or nearly equidistant from all elements in the array. Only in this way is it possible to correct measured pressure properly for the distance that the sound has traveled and to have sounds from each element arrive simultaneously at the detector.

In seismic exploration, the pressure output of a marine source is measured by an experiment called a far-field signature test. As shown in Figure 5, the detector is a hydrophone centered under the array. The term "far-field" refers to the depth of the hydrophone relative to array size and measurement bandwidth. In essence, far field means that the hydrophone is far enough away so that sounds from individual guns reach it within one sampling interval. For an average array and a 1-ms sampling interval, far-field distance is about 300 m. An additional 300 m is required between the hydrophone and the water bottom to prevent reflected sound from interfering with the measurement.

The SEG-approved unit for far-field strength of an array is the bar-m. A bar is a unit of pressure, equivalent to 14.5 psi (about 1 atmosphere) or 10^{11} μPa (micro-Pascal). The bar-m unit is obtained by multiplying measured pressure expressed in bars by the distance between the sensor and the sound source. The advantage of the bar-m unit is that source strength is characterized by a single number rather than by two numbers (the pressure and where it was measured). In the far field, peak-to-trough strength in bar-m can be converted to actual peak positive pressure at any distance by taking half the peak-to-trough number and dividing by that distance. For example, at 300 m a peak-to-trough 60 bar-m source creates a peak positive pressure of 0.1 bar [.5(60/300)]; at 1000 m it creates a peak positive pressure of 0.03 bar [.5(60/1000)].

Maximum peak pressure of an air-gun array. What is the peak positive pressure at 10 m or 1 m below an array or at any distance to the side? Those and similar questions can be important when trying to determine the impact of a marine source on the environment, especially in shallow water. In fact, interesting questions are "What is the maximum peak pressure to which an animal could be exposed near an air-gun array?" and "Where does that pressure occur?" They cannot be answered simply by applying the distance conversion from bar-m to bar to a far-field measurement. The simple conversion fails because, at the locations in question, the shape of the signature changes, not just its overall scale.

Signature shape changes near an array or to its side due to the "array effect." Consider, for example, what would happen if the hydrophone in Figure 5 were 300 m aft of the source rather than directly below it. Distances A and B would no longer be equal and peak pressures arriving at the phone from the corresponding guns would no longer coincide in time. The signature's direct arrival would then be defocused or spread out, with lower amplitude due to the noncoincident peak arrival times. The same sort of signature shape distortion occurs at any location other than at a far-field distance directly below an array. Consequently, maximum peak pressure produced by an air-gun array cannot be established simply by scaling far-field measurements.

Nevertheless, establishing minimum peak pressure for an array is quite easy: Select the largest single gun. Measure (or calculate) its peak pressure in bar-m at a convenient location. Scale that to absolute pressure at 1 m.

With a single air gun, simple distance conversion is valid because there are no array effects that change the peak pressure as location changes. With the guns currently used in the seismic industry, minimum peak pressure within an array is typically between 2 and 3 bar. Maximum peak pressure created by an array is determined by how two competing phenomenon interact. On one hand is the focusing effect due to array geometry, and on the other is the inverse scaling of pressure with distance from a source. So, the question becomes: Can array focusing effects more than compensate for the inverse scaling to produce sound levels greater than 2-3 bar, and if so, what is the spatial extent of such sound levels?

To answer these questions requires special air-gun source measurements or detailed modeling of an air-gun source. For this paper, I have resorted to air-gun modeling because it is much simpler and less costly than field measurements. The main advantage of modeling is that it allows calculation of pressure produced by an array at any underwater location. Thus, one can easily map the full 3-D extent of an array's pressure field, an exercise that would take days of field measurements to accomplish.

The modeling software, used in the seismic industry for more than 15 years, uses coupled partial differential equations to represent the interacting, oscillating air bubbles produced when an array is fired. As shown in Figure 6, modeled signatures agree quite well with measured signatures. The modeled signature in Figure 6 was calculated as if all air guns fired simultaneously. In an actual array, however, firing times are spread over 1-2 ms due to mechanical variations in their firing mechanisms. Because of this difference, the peak pressure of the modeled signature is somewhat larger than that of the measured signature.

The particular array modeled is one designed by Western Geophysical. It consists of 24 air guns arranged in three identical strings. The strings are deployed in a horizontal plane 6 m below the water surface. Each string has six source elements. The first two elements of each string consist of two air guns each, arranged in a cluster. (A cluster means guns so close together that when fired they behave as a single larger gun.) The final four elements of each string are single air guns. All guns are sleeve guns with a compressed air reservoir at a pressure of 2000 psi prior to firing. Total volume of the array is 2250 in^3, and far-field peak strength is about 57 bar-m.

Table 2 shows gun volumes and source element horizontal coordinates. Figure 7 shows a plan view of the array. In Table 2 the terms in-line and cross-line refer to the direction the ship sails and the perpendicular to the sail direction, respectively. Note that the origin of the horizontal coordinate system coincides with the most forward element in the center string. Modeled pressure results are tabulated in the same coordinate frame. Note also that the array is symmetric about the center string in the cross-line direction. This means that pressures need to be modeled for only one half of the array (the starboard side was chosen), since they, too, will be symmetric.

The first modeling experiment computed peak positive sound pressures in the horizontal plane of the array. This was accomplished by posi-

Table 3. Peak positive pressure (bar) in the horizontal plane of the array in Figure 7

In-line (m)	Crossline = 0 m	= 2 m	= 5 m	= 8 m	= 12 m	= 15 m
-10.0	0.94	0.80	0.79	0.76	0.48	0.40
-7.5	1.21	1.04	1.15	1.00	0.61	0.57
-5.0	1.53	1.35	1.49	1.33	0.83	0.74
-2.5	2.05	1.83	1.94	1.78	1.39	0.97
0.0	—	2.50	2.82	2.50	2.48	1.41
2.15	3.87	3.00	3.79	3.00	2.98	1.90
4.3	—	3.08	4.25	3.14	3.03	2.12
6.0	4.65	3.11	4.00	3.14	3.09	2.11
7.7	—	3.34	4.20	3.34	3.30	2.10
9.05	5.45	3.43	4.75	3.43	3.39	2.37
10.4	—	3.45	4.26	3.44	3.41	2.13
11.65	5.30	3.29	3.98	3.29	3.25	1.99
12.9	—	2.90	3.31	2.90	2.86	1.65
13.95	4.71	2.41	3.03	2.41	2.38	1.52
15.0	—	1.95	2.45	1.95	1.92	1.23
17.5	1.50	1.30	1.63	1.33	0.97	0.81
20.0	1.14	0.99	1.12	0.99	0.58	0.56
22.5	0.91	0.78	0.87	0.75	0.42	0.44
25.0	0.75	0.65	0.66	0.58	0.35	0.33

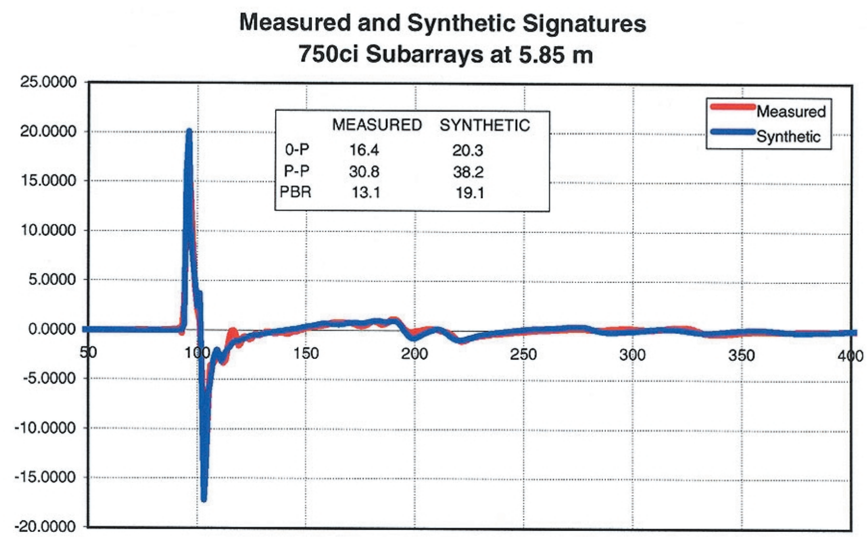

Figure 6. Comparison of measured and modeled signatures for a small air-gun array.

Table 4. Peak positive pressures at additional locations within the central gun string

In-line (m)	Crossline = 0 m
1.0	4.97
1.5	4.02
2.8	3.97
3.3	4.31
5.3	5.11
6.7	5.05
8.7	5.68
9.4	5.67
11.4	5.45
11.9	5.26

Table 5. Peak pressures below the central gun string

In-line (m)	Depth =		
	6 m	7 m	8 m
-2.5	2.05	2.19	2.18
0.0	—	4.61	2.84
2.15	3.87	3.51	3.39
4.3	—	4.26	3.66
6.0	4.65	3.77	3.55
7.7	—	4.69	3.62
9.05	5.45	4.27	3.73
10.4	—	4.85	3.59
11.65	5.30	4.31	3.20
12.9	—	4.50	2.82
13.95	4.71	3.71	2.48
15.0	—	3.54	2.26
17.5	1.50	1.58	1.63

Table 6. Peak positive pressures in a vertical line below the center of the array

Depth (m)	In-line = 9.05 m
6	5.45
7	4.27
8	3.73
9	3.47
10	3.39
12	3.42
14	3.10
17	2.78
20	2.56
25	2.06
30	1.88

tioning strings of 19 imaginary hydrophones at cross-line coordinates 0, 2, 5, 8, 12, and 15 m. The hydrophone strings, parallel to the in-line direction, had phones every 2.5 m from in-line coordinates -10 to 25 m. Note that the pattern monitors pressures inside and outside the array. Results are shown in Table 3. The pink shaded area is outside the boundaries of the array. The empty cells in the second column from

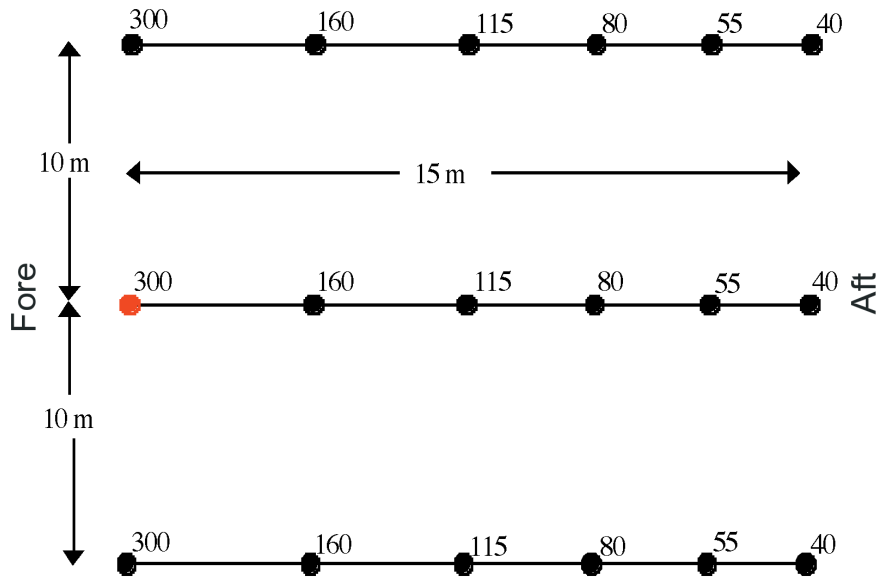

Figure 7. Plan view of the air-gun array used for the modeling study. Numbers next to each gun site are gun volumes (in^3). Red circle marks the origin of the coordinate frame.

the left correspond to coordinates where the pressure could not be computed because an air gun was too close. The largest peak positive pressure for this modeling experiment (yellow cell) occurs near the center of the middle gun string. A number of conclusions are immediately apparent:

- The largest pressures occur inside the boundaries of the array
- Outside the boundaries, pressures decay rapidly due to inverse scaling
- The largest pressure occurs near the very center of the array
- The moderately higher pressures at 5 m compared to 2 or 8 m is an indication of a focusing effect
- Focusing effects are relatively weak. At no point does pressure rise much above what one would expect by placing a hydrophone midway between two guns

The second experiment examined additional locations within the middle gun string. Results are in Table 4. The yellow cell marks the maximum peak positive pressure found for this array among all of the modeling experiments. Note that the largest positive peak pressure within the plane of the array remains below 6 bar. The third experiment examined pressures at near-field locations below the horizontal plane of the array. Based on the results in Tables 3 and 4, it is evident that maximum peak pressures occur in the center of the array. Therefore, the third experiment was restricted to the vertical plane containing the middle gun string. Results are in Table 5. The 6-m results (at the central string) are copied from Table 3 for comparison. Clearly, inverse scaling reduces the pressure more rapidly than array focusing increases pressure.

The final experiment examined peak pressure below the 9.05-m position in the central gun string over an extended depth range. (9.05 m was chosen because it is between the two locations in Table 4 with the highest pressures.) Table 6 shows the results along with the 6-, 7-, and 8-m results from Table 5.

Once again, array focusing was not able to overcome the decrease in pressure due to inverse scaling.

Discussion. A few caveats are in order. First, the modeling did not include effects of sound reflected upward from the water bottom. Generally, such energy is quite weak compared to the sound produced directly from an array. However, if an array is within 1 m of the water bottom, upward reflected energy can contribute significantly to peak pressure. Second, the array had cross-line spacing between elements (10 m) that was significantly greater than average in-line spacing between elements (3 m). If cross-line spacing had been much smaller, say 3 m, the maximum peak positive pressure would be that due to contributions from four air guns rather than that from just two air guns. In both situations, peak pressure would be higher than reported here. Third, peak pressures created by air guns depend on the bandwidth used for the measurement or calculation. The results reported here were computed for a 1-ms sampling interval (corresponding to a 500-Hz bandwidth) that encompasses most energy produced by an array. A broader band, however, may give slightly larger pressure results.

The maximum peak positive pressure was 5.68 bar at the center of the horizontal plane containing the array. This is about the pressure that should be expected by placing a phone midway between the 115-in^3 and 80-in^3 guns with all other guns turned off. The reason that the pressure peaks here rather than between the 300-in^3 and the 160-in^3 guns is the different gun separations. The two smaller guns are only 2.7 m apart while the two larger guns are 4.3 m apart. Similar modeling was done for the Schlumberger array in Figure 4. That array had a maximum peak pressure of about 7 bar between the first two gun stations of the center string.

Array focusing effects are evident in the modeled results. For example, Tables 3 and 6 show that pressure decreases slower with vertical distance below the center of the array than with horizontal distance to the side. That is exactly the behavior expected from an array whose elements are in the horizontal plane. Nowhere within or around the array was the focusing effect strong enough to overcome the decrease in pressure due to inverse scaling and produce a pressure greater than that expected between two guns.

These results suggest a general procedure for determining maximum peak positive pressure of arrays similar to the one modeled: Measure (or calculate) the pressure at various points between closely spaced adjacent guns in the plane of the array. Exact gun sizes and separations will determine which pair produces the maximum pressure. An upper limit can easily be established simply by doubling the peak pressure at 1 m from the largest gun in the array. Unless an array contains guns significantly larger than those in the modeled array, the upper limit of the maximum peak positive pressure should be around 6 bars (measured in a 500-Hz bandwidth).

Concluding remarks. Modeling shows that peak maximum pressure produced by an array is roughly a factor of 10 less than what one would expect by naively scaling a far-field measurement back to 1 m. While it is comforting to know that a 100 bar-m array does not produce pressure of 100 bar in the water, that by itself does not lead to any conclusions regarding the impact of air guns on marine animals. That impact likely depends on a number of phenomena upon which I haven't even touched in this introductory paper. For example, each species of mammals may be most sensitive to sound in a particular bandwidth. Because sound produced by an array is not distributed evenly across the frequency spectrum, some species may be bothered more by air guns than others. In addition, the sound from an array that an animal at some distance actually experiences depends on the interaction between the array, the near-surface geology, and the water depth. This is particularly true for arrays in shallow water, where changes in water-bottom conditions or water depth can create dramatic changes in the modal propagation of sound in the water layer.

Because of their reliability and favorable sound characteristics, nearly all marine seismic surveys in the past 20 years have used tuned air-gun arrays. During that time, the seismic industry has learned much about air guns: the characteristics of the sound they produce, how to measure that sound reliably, how to design optimal arrays, and how to calculate the sound from an array. That accumulated knowledge can make an important contribution to studies involving the marine environment and man-made noises. I hope that if everyone concerned with the environment works together, it won't be overlooked.

Suggestions for further reading. "A comprehensive method for evaluating the design of air guns and air-gun arrays" by Dragoset (*TLE*, 1984). "A standard quantitative calibration procedure for marine sources" by Fricke et al. (GEOPHYSICS, 1985). "Air-gun array specs: A tutorial" by Dragoset (*TLE*, 1990). *The Marine Seismic Source* by Parkes and Hatton (D. Reidel Publishing, 1986). "Desired seismic characteristics of an air gun source" by Larner et al. (GEOPHYSICS, 1982). *Marine Mammals and Noise* by Richardson et al. (Academic Press, 1995).

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